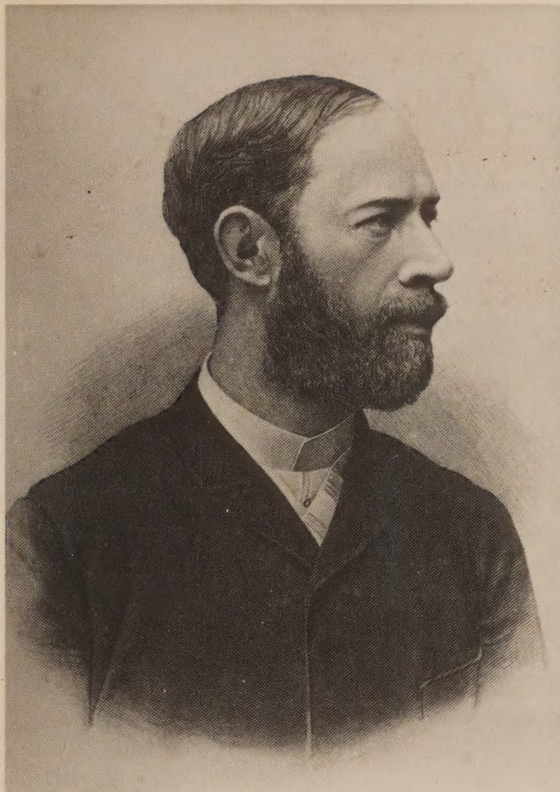

Heinrich Hertz

THE BEGINNING OF MICROWAVES

BY JOHN H. BRYANT

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IEEE Catalog No. 88TH0221-2
ISBN 0-87942-710-8

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THE BEGINNING OF MICROWAVES

BY JOHN H. BRYANT

Discovery of Electromagnetic Waves
and Opening of the Electromagnetic Spectrum
by Heinrich Hertz in the Years 1886-1892

1988 IEEE/MTT-S HERTZ CENTENNIAL CELEBRATION

ACKNOWLEDGEMENT

The 1988 IEEE/MTT-S Hertz Centennial Celebration, consisting of the exhibition at the 1988 MTT-S International Microwave Symposium and this publication, was made possible by the generous contributions of the following organizations:

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Institute of Electrical and Electronics Engineers, Life Members Fund ($10,000 Donation)
IEEE/Microwave Theory and Techniques Society ($10,000 Donation)
1988 IEEE/MTT-S International Microwave Symposium Steering Committee ($5,000 Donation)

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Heinrich Hertz
1857-1894

Background

In 1864 James Clerk Maxwell (1831-1879) produced a thoroughly new way of thinking about electricity and magnetism. It incorporated almost all prior results and placed them in a novel context, in the universal language of mathematics — in the form of equations — Maxwell's equations. A solution to the equations is periodic in space and in time — in other words, a wave. The velocity of the wave is given by the product of wavelength times frequency. A numerical value for the velocity also comes from the solution — 3×10^8 meters per second. It was recognized that this was very close to the velocity of light, which had been measured to within a few percent of the value accepted today.

There was a 22-year interval between the delivery of the paper "On a dynamical theory of the electromagnetic field" by Maxwell in 1864 [1] and the start of successful experiments in November 1886 by Heinrich Hertz (1857-1894) to validate the theory [2]. Public recognition of Hertz's results came in mid-1888 on publication of his paper with "waves in air" in the title [3].

Maxwell's theory says that energy can be transported through dielectrics, including empty space, at a finite velocity by electric and magnetic fields traveling together in space at right angles to each other and both at right angles to the direction of travel. Maxwell never published a proposed experiment to validate his radical theory, opposed by most scientists. According to Maxwell what happened in space far from conductors was a key to his theory, in direct opposition to the generally accepted theory of action-at-a-distance with infinite velocity of propagation. The few scientists who tried to understand Maxwell had difficulty comprehending what he said, much less understanding what the equations implied.

Hertz's career

Hertz started out to be an engineer. On graduation from the Gymnasium (high school) in 1875 he spent a year with a civil engineering firm in Frankfurt. In April 1876 he enrolled in engineering at the Dresden Technical Institute, but left on 30 September 1876 for his year of mandatory military service — with the First Railway Guards Regiment in Berlin.

He enrolled in physics in October 1877 at the University of Munich, and attended some lectures at the Technical University. In October 1878 Hertz transferred to the University of Berlin and studied under Hermann von Helmholtz and Gustav Kirchhoff.

Paving the way to understanding and use of Maxwell's work: the Berlin prize problem

Helmholtz had been trying to understand Maxwell's theory of electromagnetism and to compare it with a theory, based mostly on Newtonian mechanics, attributed especially to Fritz Neumann and Wilhelm E. Weber in Germany. In 1879 Helmholtz called for an experimental validation of Maxwell's theory and had it published as a prize problem of the Prussian Academy of Science (Berlin) in 1879 [4], often referred to as the *Berlin Prize*. The translated full text is as follows:

> Mr. Mommsen, the presiding secretary for the day, opened the meeting with the speech of the day. He spoke on Leibniz's importance as an historian and on his achievements in the publication of source material and in historiography.
> Mr. du Bois-Reymond gave a report on the prize in the physical-mathematical class which is to be paid out of the Ellert legacy.
> The Academy poses the following question for the 1882 prize:
> The theory of electrodynamics which was brought forth by Faraday and was mathematically executed by Mr. Cl. Maxwell presupposed that the formation and disappearance of the dielectric polarization in insulating media — as well as in space — is a process that has the same electrodynamic effects as an electrical current and that this process, just like a current, can be excited by electrodynamically induced forces. According to that theory, the intensity of the mentioned current would have to be assumed equal to the intensity of the current that charges the contact surfaces of the conductor. The Academy demands that decisive experimental proof be supplied either
>
> for or against the existence of electrodynamic effects of forming or disappearing dielectric polarization in the intensity as assumed by Maxwell
>
> or
>
> for or against the excitation of dielectric polarization in insulating media by magnetically or electrodynamically induced electromotive forces.
>
> Answers to this question have to be submitted by March 1, 1882. Submissions may, at the author's discretion, be written in German, Latin, French or English. Each submission has to bear a motto which must be repeated outside of a sealed envelope containing the author's name. The prize of 100 ducats= 955 marks will be awarded at the public meeting of the Academy on the Leibniz anniversary in July 1882.

Helmholtz thought that one of his students, Heinrich Hertz, would be the most likely to succeed in experimentation. In 1892 Hertz wrote:

> As I was at the time [1879] engaged upon electromagnetic researches at the Physical Institute in Berlin, Herr von Helmholtz drew my attention to this problem, and promised that I should have the assistance of the Institute in case I decided to take up the work. I reflected on the problem, and considered what results might be expected under favorable conditions by using the oscillations of Leyden jars or of open induction coils. The conclusion at which I arrived was certainly not what I had wished for; it appeared that any decided effect could scarcely be hoped for, but

> only an action lying just within the limits of observation. I therefore gave up the idea of working at the problem; nor am I aware that it has been attacked by anyone else. But in spite of having abandoned the solution at that time, I still felt ambitious to discover it by some other method; and my interest in everything connected with electric oscillations had become keener. It was scarcely possible that I should overlook any new form of such oscillations, in case a happy chance should bring such to my notice [5].

Hertz did an analytical thesis on the induced currents in a rotating metal sphere in a magnetic field [6] and obtained his doctorate in 1880. Numerous entries in his diary [7] show that he did in fact give a great deal of thought to electromagnetics in the intervening years to 1886.

After graduation in 1880, Hertz stayed on as an assistant to Helmholtz for three years, then went to the University of Kiel as an instructor in theoretical physics. At Kiel, Hertz had no laboratory, and was very impatient working only in theoretical physics. Even as a boy he had had his own home workshop. Hertz built instruments and was very interested in experimentation, remaining equally skilled at both experimentation and analytical work.

In 1884, at Kiel, Hertz published a significant paper, "On the relations between Maxwell's fundamental electromagnetic equations and the fundamental equations of the opposing electromagnetics." It led him to believe more strongly in Maxwell's theory, and gained recognition from his superiors. In the 1884 paper he concluded that if he had to make a choice, he would choose Maxwell's theory:

> I have attempted to demonstrate the truth of Maxwell's equations by starting from premises which are generally admitted in the opposing system of electromagnetics, and by using propositions which are familiar in it. Consequently I have made use of conceptions of [the opposing theory]; but, excepting in this connection, the deduction given is in no sense to be regarded as a rigid proof that Maxwell's system is the only possible one. It does not seem possible to deduce such a proof from our premises . . . I think, however, that from the preceding we may infer without error that if the choice rests only between the usual system of electromagnetics and Maxwell's, the latter is certainly to be preferred . . .

He went on to give reasons [8]. The paper helped him get his next and most important appointment, at Karlsruhe in 1885.

On 29 March 1885 Hertz moved to Karlsruhe as a professor. Here his life changed. He had his own department, including a laboratory, shop, and some staff [9]. On 31 July 1886 he married Elizabeth Doll, the daughter of a faculty colleague, and started successful electromagnetic experiments later that year.

---

1. James Clerk Maxwell, "A dynamical theory of the electromagnetic field," Phil. Trans. Royal Soc. (London), vol. 155, pp. 459-512; 1865 (received Oct. 27, read Dec. 8, 1864).
2. Johanna Hertz, *Heinrich Hertz, Memoirs, Letters and Diaries,* revised edition prepared by Mathilde Hertz and Charles Susskind, San Francisco Press, Inc. and Physik Verlag, GmbH, 1977.
3. Heinrich Hertz, "On electromagnetic waves in air and their reflection," *Electric Waves,* Chap. 8, D.E. Jones translation, London, Macmillan and Co. (1893), and New York, Dover, (1962).
4. Monthly Report of the Prussian Academy of Sciences in Berlin, (in German), pp. 519, 528 and 529, July 1879.
5. Heinrich Hertz, *Electric Waves,* pp. 1 and 2.
6. Heinrich Hertz, "On induction in rotating spheres" (1880), Chapter 2, *Miscellaneous Papers,* D.E. Jones and G.A. Schott translation, London, Macmillan and Co., 1896.
7. Johanna Hertz, *op. cit.*
8. Heinrich Hertz, *Miscellaneous Papers,* Chap. 17.
9. Otto Lehmann, *History of the Technical Institute of the Techn. Hochschule Karlsruhe* (in German), 1892.

Introduction

The Institute of Electrical and Electronics Engineers (IEEE) Microwave Theory and Techniques Society (MTT-S) Hertz Centennial celebrates the anniversary of the historic experiments of Heinrich R. Hertz, from 1886 to 1891, using what are now called microwave circuits and techniques. His remarkably thorough investigations validated Maxwell's theory of electromagnetism (1864) and opened up the RF portion of the electromagnetic spectrum between DC and light for scientific and practical uses. He arrived at his results by a step-by-step learning process, alternating between experiments and analytical work. A chronology of Hertz's experiments and published papers in electromagnetics is given on p. 50.

Hertz's unusual grasp of theory, added to his insight, enabled him to translate theory into concepts. With equally unusual abilities as an experimenter, Hertz transformed concepts into apparatus and conducted some of the most important experiments in the history of science. He validated Maxwell's theory, whereas neither Maxwell himself, nor any of Maxwell's successors in the intervening 22-year period, had been able to consummate an experiment. Hertz continued with extensive experiments, combined with analytical work.

Hertz's experiments were the first knowledgeable and purposeful use of the RF spectrum. He first had to learn how to generate and detect electric waves. His progress led him to use distributed circuits, at 50 MHz (6 m wavelength), 100 MHz (3 m wavelength), and later at 500 MHz (60 cm wavelength).

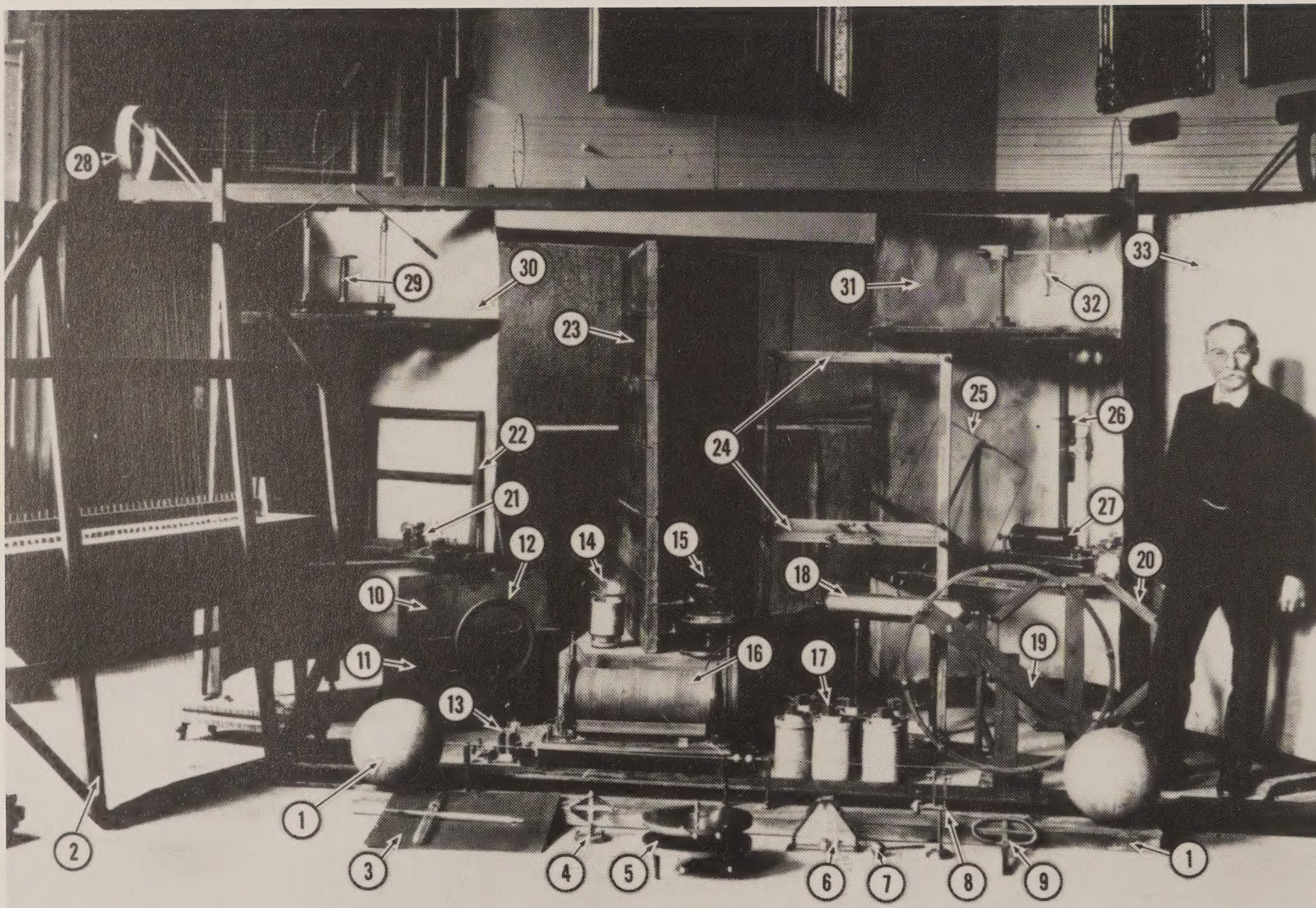
The items of apparatus designed by Hertz and built by an assistant and himself are notably elegant in their simplicity and functional capability. For the most part they were built of inexpensive materials: metal sheet and wire, wood, glass, string, and sealing wax.

Around 1913 the Hertz apparatus was transferred to the Deutches Museum in Munich. In the late 1920s, a model maker in Munich, Julius Orth, built three sets of replicas, working from the originals, for: (1) the Science Museum, London, (2) the National Radio Society in Berlin (status of the items unknown at present), and (3) the 1933 World's Fair in Chicago (after which the items went to the Museum of Science and Industry there). About half of the Chicago items survive.

The London set is intact, and was refurbished for exhibit at the IEEE 1988 MTT-S International Microwave Symposium, May 25-27, in New York City, and the MIT Museum in Cambridge, Massachussetts, during the summer and fall before their return to London in late 1988.

This book is laid out in chronological order, as nearly as possible, to demonstrate Hertz's step-by-step discovery and learning process.

Some of the photographs used are of the replicas in the London set, as noted. A comparison with photographs of the originals, pages 10, 23 and 39, speaks for the replicas as representative of the original pieces in size, shape, construction, and therefore in functional detail.



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Hertz's Apparatus and Laboratory Equipment

The photograph shows original apparatus built by Heinrich Hertz for his electromagnetics experiments, along with items of laboratory equipment. Page numbers are given where items are described in the text.

1. First oscillator/radiator transmitter, signal source, 6 m wavelength, pp. 18 and 23.
2. Wooden frame and parallel wires for polarization demonstration, both transmission and reflection, 39 and 42.
3. Possibly a demountable vacuum apparatus for cathode-ray experiments.
4. Hot-wire galvanometer.
5. Knochenauer spirals, p. 14.
6. Rolled-paper galvanometer, p. 46.
7. Metal sphere with insulated handle, p. 23.
8. A Reiss's spark micrometer.
9. Receiver/detector used with coaxial transmission line experiments, 6 m, p. 33.
10, 11 & 12. Apparatus to demonstrate polarization effects in insulators, 6 m, p. 26.
13. Mercury interrupter.
14. Meidinger cell (primary battery). Same chemistry as the Daniell cell. May also be seen in photograph on p. 23.
15. Vacuum bell jar, photoelectric effect experiments, p. 24.
16. Induction coil, p. 23.
17. Bunsen cells (primary batteries).
18. Large-area conductor, insulated for high voltage, used for storing electric charge. Variously referred to as the "primary" conductor for a high-voltage electrostatic generator, or as a "capacitor". May also be seen in photograph on p. 23.
19. Circular-loop receiver, 6 m, p. 34.
20. Receiver/detector, not otherwise identified.
21. Rotating mirror and mercury interrupter assembly.
22. Square-loop receiver, 6 m.
23. Stack of three wedge-shaped wooden boxes to hold dielectric material for refraction demonstration and dielectric constant measurement, pp. 39 and 43.
24. Assembly of two square-loop receivers, 6 m, p. 23.
25. Square-loop receiver, 6 m.
26. Transmitter dipole, 70 cm, p. 38.
27. Induction coil, p. 39.
28. Coaxial transmission line, p. 33.
29. Discharging table, similar to a Henley's discharger. May also be seen in photograph on p. 23.
30. Cylindrical parabolic reflector/receiver, 60 cm, pp. 39 and 41.
31. Cylindrical parabolic reflector/transmitter, 60 cm, pp. 39 and 40.
32. Circular-loop receiver, 3 m.
33. Plane metal reflector, pp. 39 and 43.

Photograph taken October 1, 1913 in the auditory of the Bavarian Academy of Science, in Munich. (Courtesy of the Museum of Science and Industry, Chicago). The individual in the photograph is not identified, but possibly he was an employee of the Deutsches Museum.

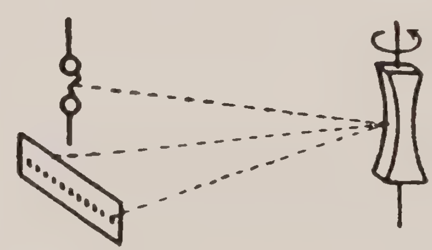
Electrical History: High Frequency Alternating Currents

To appreciate fully the accomplishments of Heinrich Hertz, we must recall the status of electrical science up to a century ago. Electrostatic machines for converting mechanical energy to electrical energy were first used in the 17th century, and high voltage capacitors (Leyden jars) capable of storing static electricity appeared in the early 18th century. The primary battery (electrochemical cell) as a steady source of electricity was invented by Volta at the end of the 18th century.

The phenomenon of induction, in which electricity could be produced by a changing magnetic field, was discovered independently by Faraday and Henry in 1831. Mechanically driven electrical generators immediately followed. They were generally fitted with commutators to convert the low-frequency alternating current (AC) to direct current (DC) for commercial use.

The concepts of electricity in motion, and especially the generation of and use of alternating currents, developed slowly. Helmholtz, in a 1847 article [10], noted evidence of electrical oscillations:

> . . the discharge of a battery is not a simple motion of the electricity in one direction, but a backward and forward motion between the coatings, in oscillations which become continually smaller until the entire *vis viva* is destroyed by the sum of the resistances. The notion that the current of



Rotating Mirror Strobe
For Frequency Measurement
B.W. Fedderson, 1857

> discharge consists of alternately opposed currents is favored by the alternately opposed magnetic actions of same; and second, by the phenomena observed by Wollaston while attempting to decompose water by electric shocks, that both . . . gases [hydrogen and oxygen are produced] at both electrodes.

William Thomson (the future Lord Kelvin) in an 1853 paper[11] described his analysis:

> . . to determine the motion of electricity at any instant after an electrified conductor, of a given capacity, charged initially with a given quantity of electricity, is put in connection with the earth by means of a wire or other linear conductor of given form and resisting power.

He derived an expression for the current as a function of time for a circuit of capacitance C, inductance L, and resistance R. For resistence below a certain value, the circuit is oscillatory, with a half-period $T=\pi/(1/LC — R^2/4L^2)^{1/2}$. In the case where R is small enough so that the second term is substantially smaller than the first, this reduces to $T=\pi/(LC)^{1/2}$. For low frequency circuits, and with enough power so that one of the elements was heated until it glowed, Thomson noted that the oscillatory behavior could be observed by the eye. He made a prophetic suggestion:

> A corresponding phenomenon might probably be produced artificially on a small scale by discharging a Leyden phial or other conductor across a very small space of air; and through a linear conductor. . . . Should it be impossible on account of the too great rapidity of the successive flashes for the unaided eye to distinguish them, Wheatstone's method of a revolving mirror might be employed, and might show the spark as several points or short lines of light separated by dark intervals instead of . . . an unbroken line of light.. . .

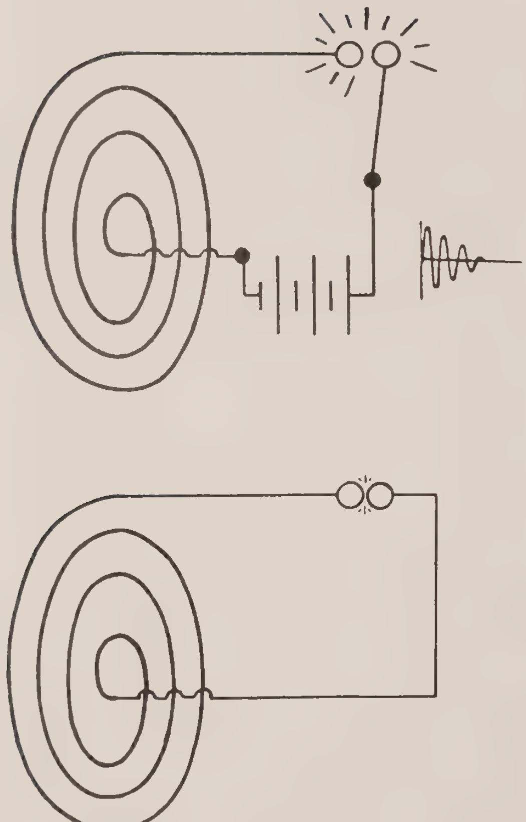
In 1857 B.W. Feddersen successfully carried out such an experiment for a doctoral dissertation at Kiel. He was able to record the succession of bright flashes on film. He could calculate the frequency of the oscillation from the speed of rotation of the mirror and the geometry, knowing that there were two flashes per cycle of oscillation. At Leipzig he continued the investigation for several years, as described in six papers in *Annalen der Physik*[12].

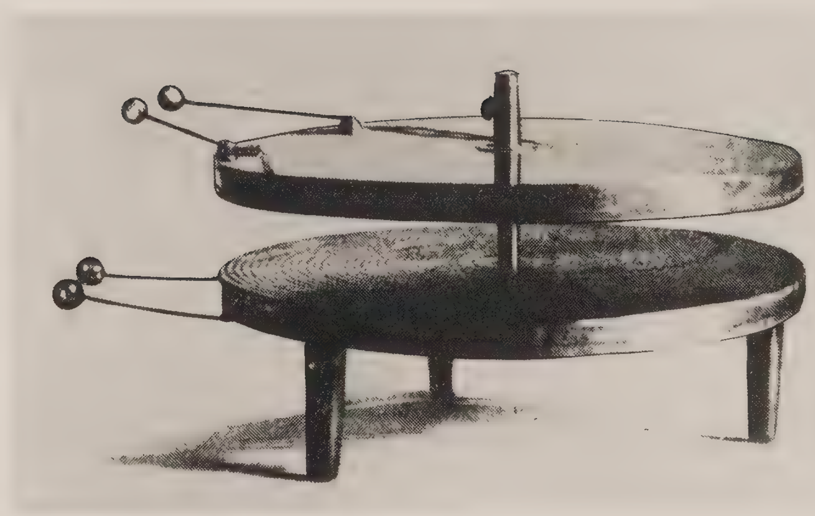
Feddersen succeeded in producing oscillations of periods as short as 1 microsecond, corresponding to a frequency of 1 MHz (wavelength 300 meters) and measured the frequency by mechanical means, the rotating mirror.

Neither Feddersen nor Thomson conceived of electromagnetic radiation at the time, and did not see that there was any component of resistence other than the dissipation of energy as heat. Only after Hertz investigated electromagnetic radiation was it realized that a radiative component of resistance existed.

---

10. Hermann von Helmholtz, "On the conservation of force," translated into English in *Scientific Memoirs Selected from the Transactions of Foreign Academics of Science and from Foreign Journals – Natural Philosophy*, pp. 114-162, edited by John Tyndall and William Francis, published by Taylor and Francis, London; 1853.
11. William Thomson, "On transient electric currents," *Phil. Mag.*, S. 4., Vol. 5, No. 34 pp. 393-405; June, 1853.
12. *Ostwald's Klassiker der exakten Wissenschaften*, Vol. 166, Th. Des Cordes, editor, Leipzig; 1908. This is a reprint of articles from *Annalen der Physik*, 2nd. ser., Vols. 103, 108, 112, 113, 115 and 116.





Discovery by Hertz of a Method to Both Generate and Detect Electromagnetic Energy (Electric Waves)

Among the equipment in the laboratory at Karlsruhe was a set of Knochenhauer spirals [item 5 on p. 10]. They are flat spiral coils of copper wire, with no iron present. While experimenting with this apparatus, Hertz discovered how to generate and detect electromagnetic energy.

At each end of these two coils is a spherical ball. If a battery is connected across the top terminals and then the circuit is opened, a spark occurs. The eye sees and the ear hears a spark, but human senses are not fast enough to know that the discharge is oscillatory. However, each time that a spark was drawn at the top coil, which Hertz referred to as the *primary*, a spark simultaneously occurred across the close-spaced terminals of the bottom coil, the *secondary*. A further observation convinced him that he was on the right track:

> At first I thought the electrical disturbances would be too turbulent and irregular to be of any further use; but when I discovered the existence of a neutral point in the middle of a side-conductor, and therefore of a clear and orderly phenomenon, I felt convinced that the problem of the Berlin Academy was now capable of solution[13].

According to Hertz[14], the typical frequency of oscillation of a laboratory coil is around 10 kHz (wavelength 3 kilometers), and for a typical laboratory capacitor known as a Leyden jar it is about 1 MHz (300 meters wavelength). Even the latter wavelength was much too long for apparatus to be used in the laboratory. Hertz needed a signal source and detector operating at much higher frequency.

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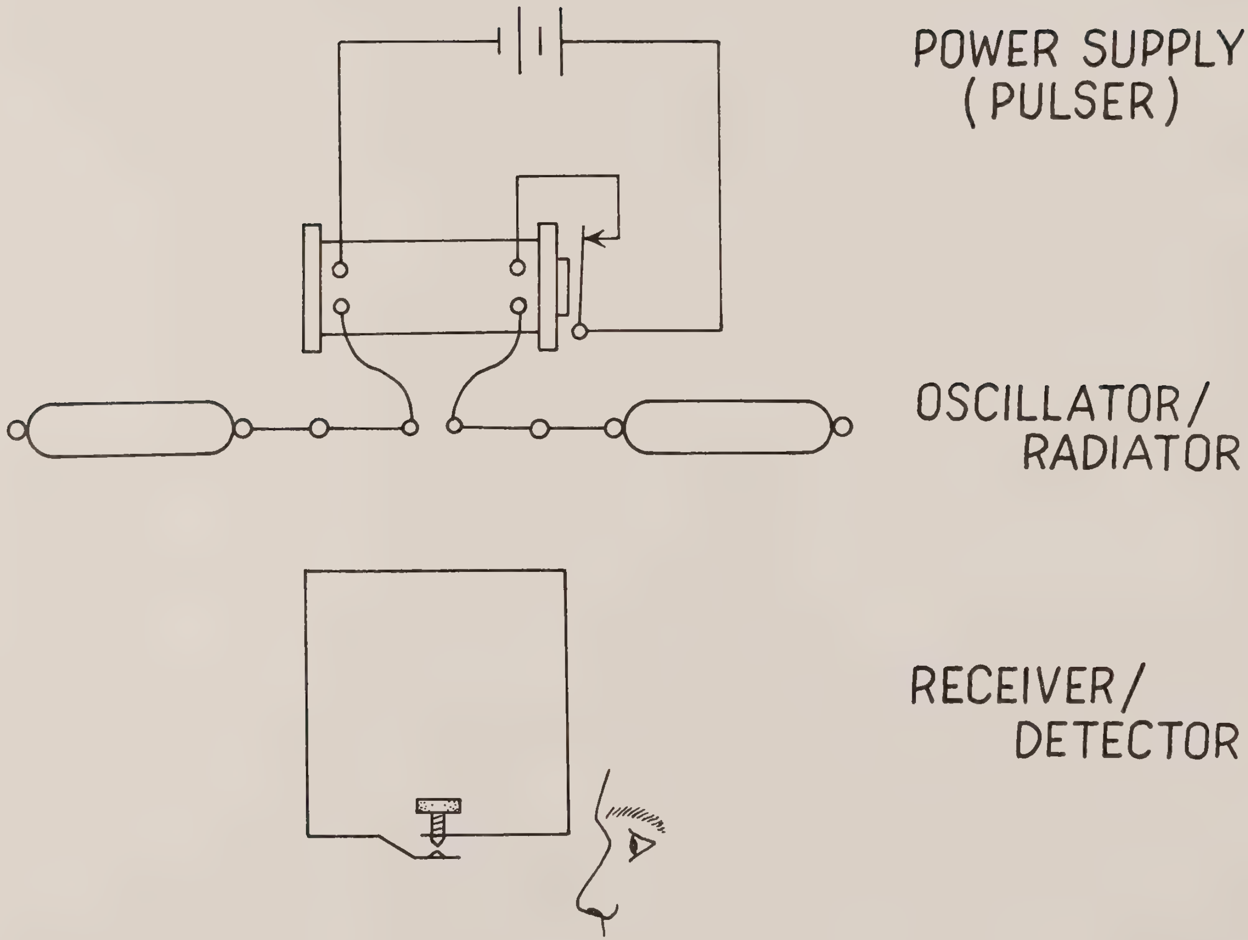
13. Hertz, *Electric Waves*, p. 2.
14. Hertz, *Electric Waves*, Chap. 2, p. 29.


POWER SUPPLY
(PULSER)
OSCILLATOR/
RADIATOR
RECEIVER/
DETECTOR

First RF Circuits and Their Use: Concept

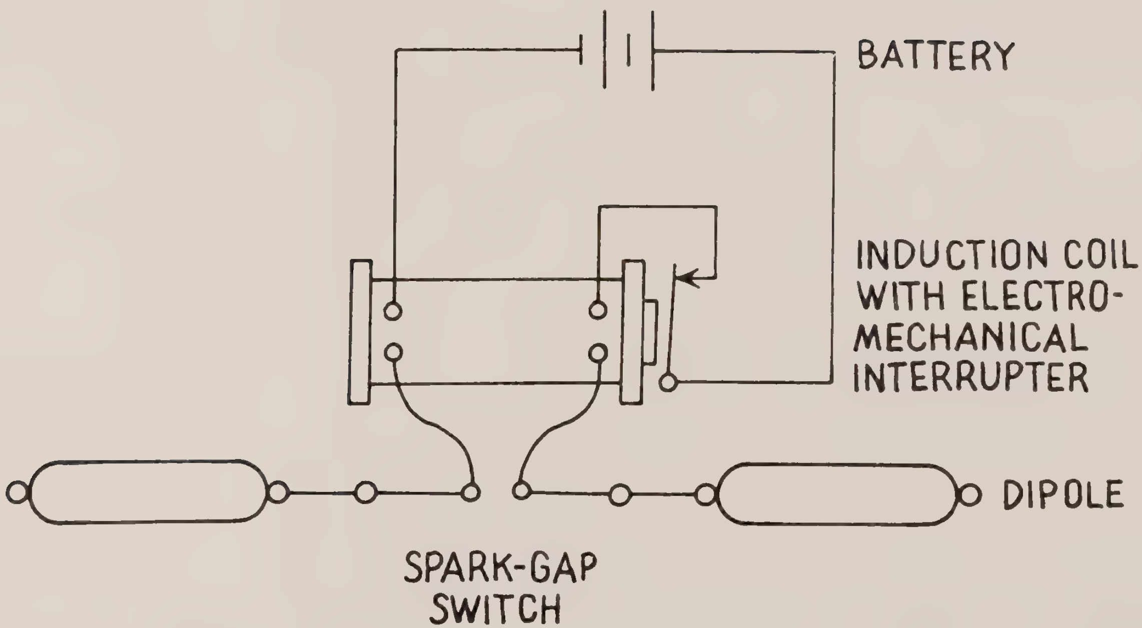
For his high-frequency apparatus, Hertz invented resonant "open" or distributed (microwave) circuits. He referred to the RF circuit arrangement shown at left as a transformer, reminiscent of the two flat spirals. The oscillator/radiator or signal source, which he termed the *primary*, is a balanced halfwave dipole. In the center of the dipole is a spark gap that functions only as a very fast-acting switch. Above the dipole is an induction coil and battery to supply high voltage pulses of DC potential energy, which are converted to RF energy by the oscillatory motion of current flowing on the surface of the dipole.

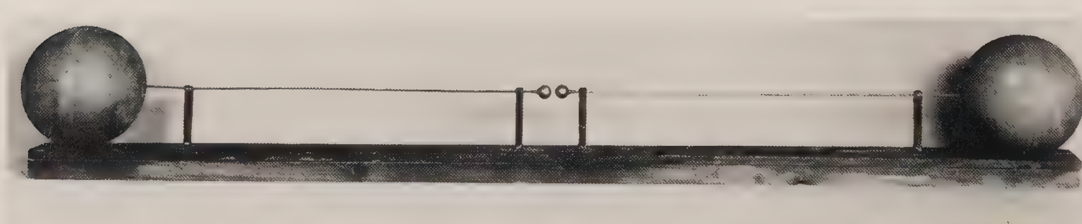
Hertz called the receiver/detector the *secondary,* and sometimes the *resonator.* It is a half-wavelength resonant loop, fitted with a tiny adjustable spark gap to detect the presence and the magnitude of RF energy radiated by the primary. The eye is used as the indicator. The primary and the secondary are linked by the electromagnetic fields in the free space.

Power Supply

For a power supply to furnish electrical energy to be converted into radio frequency (RF) energy, Hertz used available technology. The principle of the transformer had been known for about 50 years — from the work of Faraday and Henry. The induction coil, a transformer with a primary of a few turns of heavy wire and secondary of many turns of smaller wire, was then a common piece of laboratory apparatus. Electrical energy from the battery is transformed into a high-voltage DC pulse at the output terminals of the induction coil each time the interrupter breaks the circuit of the induction coil primary. A common form of the interrupter used at that time was a solenoid-operated mercury switch, referred to as a mercury interrupter. Some induction coils were fitted with an electromechanical vibrator to interrupt the current. The output terminals of the induction coil are connected across the dipole.

First RF Signal Source





Hertz's first oscillator/transmitter makes use of a resonant circuit consisting of a balanced half-wavelength dipole, capacitively loaded by the rather large (30 cm diam.) spheres made of zinc sheet. The frequency is about 50 MHz, wavelength 6 meters, half-wavelength 3 meters. The overall length is about 2 meters, with the shortening from 3 m to 2 m accounted for by the capacitive loading of the conducting spheres. The spherical balls in the center, which divide the dipole in half, are used as a very fast-acting switch.

Operating Mechanism of the Hertzian Oscillator.
When current flowing in the primary of the induction coil is interrupted, the resulting DC voltage pulse across the secondary rises, charging the capacitance of the dipole until voltage breakdown occurs across the central spark gap. The resulting arc connects the two parts of the dipole. If the arc develops fast enough (in a very small fraction of a cycle of the oscillation), the opposite ends of the dipole are momentarily of opposite charge (+ and −), and the electric field between the two ends of the dipole is maximum. When the gap breaks down, the arc has very low resistance. The quantity of stored energy at that point is the product of the voltage squared at breakdown and the capacitance of the resonant circuit (the dipole). The charge starts to redistribute itself, but cannot do so immediately owing to inductive forces on the resulting current flow. At the end of one quarter-cycle the charge has redistributed to zero, the current flow has reached maximum, and the energy is in the surrounding magnetic field. The electric field has gone to zero.

At this point the magnetic field starts to collapse, further driving the current in the same direction as before and charging the dipole in the opposite direction until the end of one half cycle. The energy is again in the electric field. The voltage between the dipole halves again breaks down the central spark gap, but in the opposite direction to that of a half-cycle before, and current flows. The charge thus flows back and forth in simple harmonic motion as the energy alternates between electric and magnetic — except that during each half cycle a *percentage* of the energy present is radiated as RF energy. The percentage radiated each half-cycle depends on the configuration of the radiating element. For a dipole it is about 15%. One therefore gets about five half-cycles of detectable RF energy from each pulse.

The DC input power to be converted into RF power each pulse is equal to the product of voltage squared at breakdown times the capacitance of the dipole (which decreases with the wavelength). For a given wavelength, the only means for increasing the input power is to increase the voltage of the pulse (up to a certain point) by a widening of the spark gap so that it will break down at a higher voltage. By computation Hertz estimated that for 36 kilovolts at breakdown the peak output power (in the first half-cycle) should be 16 kilowatts for the 6 m wavelength dipole.

In practice, the switching arc pits the spark gap electrodes, so they require frequent polishing. The sharp edges of the pits result in high fields that leak off the charge prematurely, causing erratic operation or failure of the transmitter to operate.

In subsequent experiments Hertz used apparatus operating at 3 m and one at 60 cm wavelength.

Output Waveform
The typical output voltage waveform of a Hertzian oscillator is a damped sine wave. The damping is due mostly to radiation, since radiation losses are much greater than circuit losses. The resulting pulse of RF energy is very short.

Frequency Spectrum of RF Pulses
The relation of amplitude in time and amplitude in frequency is defined mathematically by the Fourier transform. A very short pulse of RF energy results in a very wide RF frequency spectrum, a long pulse in a narrow spectrum.

First RF Receiver

Hertz's first receiver for use with the 6 m transmitter makes use of a resonant circuit consisting of a rectangular loop of wire with a small gap. At resonance the loop is electrically one-half wavelength long, and the voltage across the ends of the loop is maximum.

For a detector, Hertz fitted a tiny, adjustable spark gap across the ends of the loop to act as a voltmeter to detect the presence (and indicate the magnitude) of electromagnetic fields. The loop is polarized, with the plane of polarization in line with the gap. It is therefore a vector voltmeter, since the loop has direction sense, and the length of the gap that will just break down is a measure of the RF voltage across the gap and therefore of the field strength.

Note the mounting for optics, used for observing the small spark gap. The breakdown voltage for even a tiny gap is at least 300 volts, so that a great deal of power is involved in producing even the tiniest visible sparks.

Hertz tried a classic detector, first used by Galvani in 1800, but got no result: "Acting on friendly advice, I have tried to replace the spark gap . . . by a frog's leg prepared for detecting [DC] currents; but this arrangement which is so delicate under other conditions does not seem to be adapted for these purposes"[15]. In his earliest experiments, Hertz had noted: "No physiological effects . . . could be detected; the secondary [receiver] circuit could be touched or completed through the body without experiencing any shock"[16].

Hertz later used circular configurations of his receiver at 3 m and 60 cm wavelengths, and used a dipole at 60 cm wavelength.

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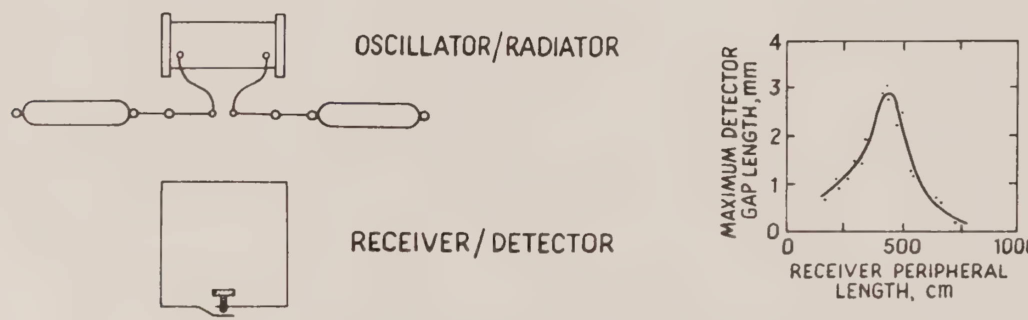
15. Hertz, *Electric Waves,* p. 185.
16. Hertz, *Electric Waves,* p. 38.

Experiments in Resonance; Coupled Circuits



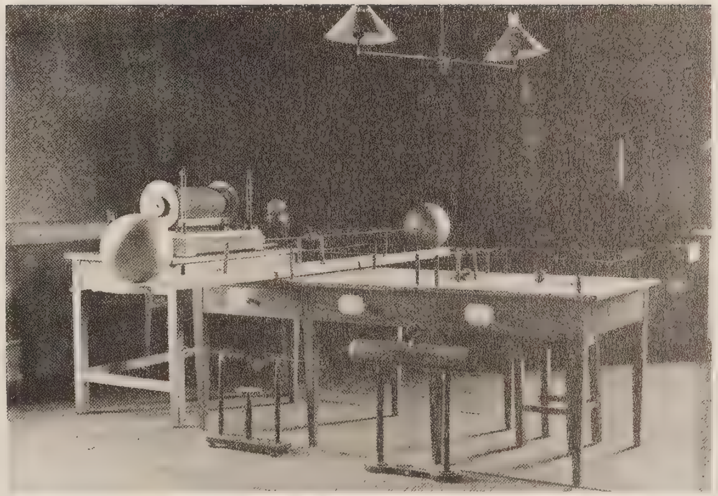
DEMONSTRATION OF RESONANCE BY HERTZ USING COUPLED CIRCUITS AND TUNING OF THE RECEIVER CIRCUIT.

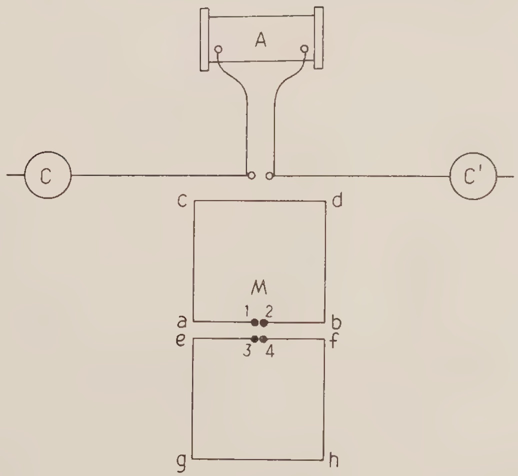
Keeping the signal source configuration constant, thus fixing the frequency, Hertz tuned the receiver over a wide range in wavelength by changing the overall length of the detector loop. He measured the maximum detector gap spacing that would just break down, a measure of the RF voltage across the gap. The shape of the curve is likely somewhat distorted due to frequency pulling of the source as the receiver was tuned. Note that at resonance Hertz was able to get a 3 mm spark to break down, and he could detect spacing down to less than 3/10mm — a voltage ratio of 10 to 1, or 20 dB.

Transmitter and Two Coupled Circuits (Receivers)

This photograph was taken in a laboratory of Hertz's Physics Institute at Karlsruhe, around 1887[17]. On the higher table at the left may be seen the induction coil, used to produce pulses of DC potential energy that is converted into RF energy by the transmitter, and the manner in which it is connected to the transmitter. The near table holds the transmitter and two rectangular-loop receivers (schematic at lower right).

In the middle of the loop on the right note the metal sphere mounted on an insulated handle, used to probe (disturb) the fields on each loop and demonstrate resonance. At the nodal points, the center of *cd* and *gh*, there is no disturbance when the sphere touches the wire. Continuing around either of the loops, sparks can be drawn from the wire and simultaneously sparks in the detector gap are diminished. The effect increases and is maximum by the detector gaps *1-2* or *3-4*.





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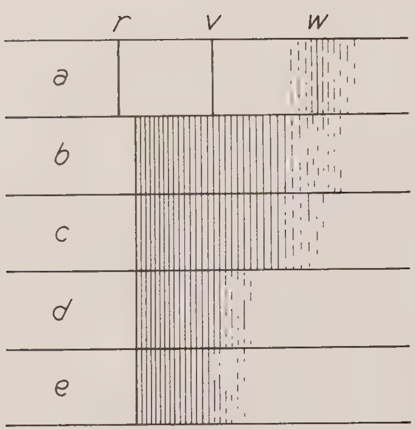
17. August Schleiermacher, "Heinrich Hertz, biographical sketch," (in German), Proc. Nat. Sci. Soc. Karlsruhe (Verhandlungen des Naturwissenschaftlichen in Karlsruhe), vol. 15, pp. 18-32, 1901/1902.


r
v
w


r v w
a
b
c
d
e

The Effect of Ultraviolet Light upon the Electric Discharge = Discovery of the Photoelectric Effect

From the start of his experiments, Hertz was bothered by a phenomenon that had an erratic effect on the detector spark gap. Whenever it was exposed to direct view of the transmitter spark, the maximum spark-length was always increased. This was especially a problem in the experiment on resonance in which Hertz needed to measure accurately the maximum length that would just break down. Other light sources gave the effect in varying degree. Even the transmitter spark gap was adversely affected by the active rays of the radiation involved. See drawing in center of p. 40. The light shield *s* was found necessary, to shield the transmitter spark gap from direct view of the corona discharge which develops in the area where the high-voltage wires pass through the reflector. He found that simple shielding would suffice in all cases, and could have left it at that.

Scientist that he was, however, Hertz realized that he was observing an important phenomenon: "A phenomenon so remarkable called for closer investigation." Hertz stopped his electromagnetic experiments to investigate, and he performed extensive experiments[18]. All metals were opaque to the radiation. Various gases, liquids, and solid dielectrics were transparent, some were partially so, and some were opaque. Air, water, quartz, and rock crystal, for example, were found to be transparent.

Hertz then used an optical spectroscope developed in 1860 by Robert Bunsen and Gustav Kirchhoff. In the photographic impression at *a* the position of the visible red is indicated by *r*, that of visible violet by *v*, and that of the strongest effect on the detector spark gap by *w* in the ultra-violet. The photographic impression at *b* results after the radiation passes through air and quartz, *c* after passing through coal-gas, *d* after passing through a thin plate of mica, and *e* after passing through glass. As noted, air and quartz were found to be transparent. The three other materials — coal gas, mica, and glass, were found to be opaque to the active rays of radiation causing the effect, although, in this photograph, coal gas appears to be less opaque than the last two.

Hertz thus identified these phenomena as being clearly associated with the ultraviolet portion of the spectrum. He had discovered the surface photoelectric effect, but he had no way of understanding it. The electron had not been discovered. Later investigators came to understand that a photon (quantum of energy) at ultraviolet wavelength has sufficient energy to free an electron from the surface of the metallic spark gap electrode, and the presence of free electrons lowers the threshold of voltage breakdown. In his paper, "On an effect of ultraviolet light upon the electrical discharge"[19], Hertz concluded: ". . . I confine myself at present to communicating the results obtained, without attempting any theory respecting the manner in which the observed phenomenon are brought about." Hertz's keen observation and skill as an experimentalist and communicator show through in this paper, which set off a new activity in physics and was the start of quantum physics.

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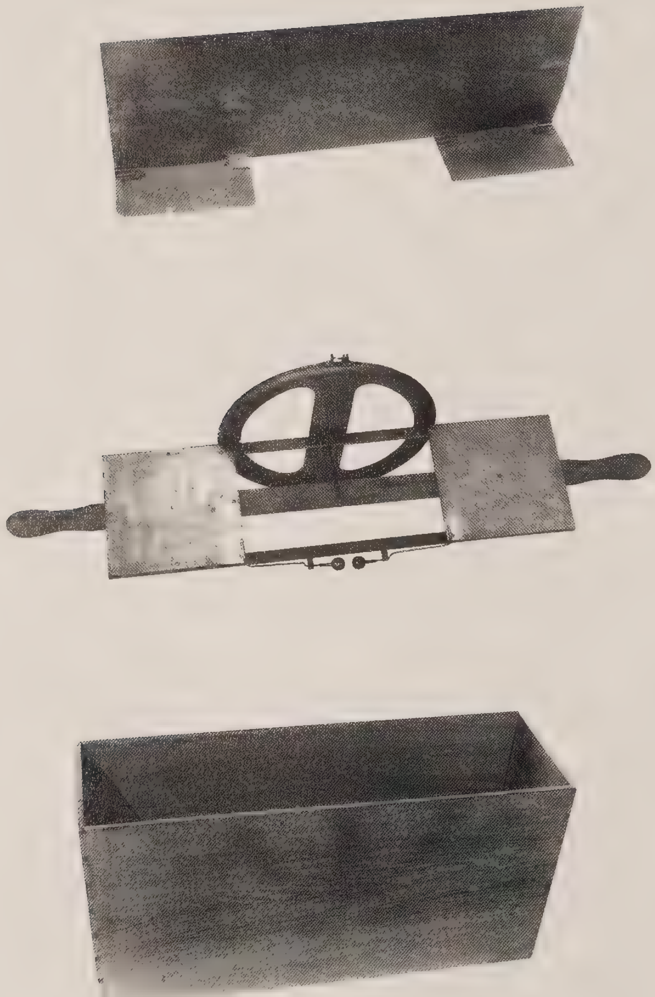
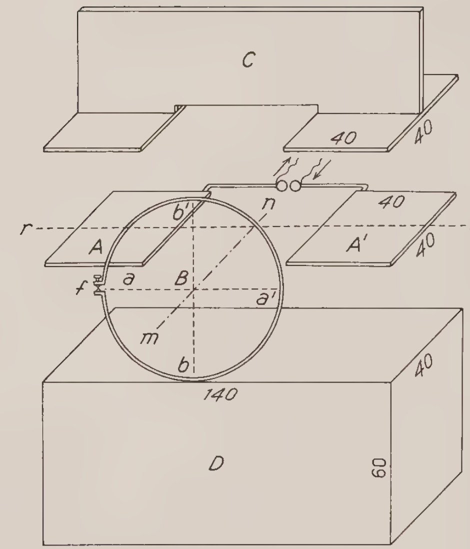
18. Hertz, *Electric Waves,* chap. 4.
19. *Electric Waves,* Chap. 4.





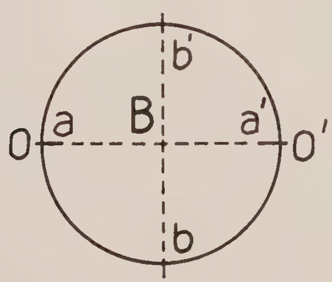
C
40
40
40
n
b'
r
S
A
A'
40
f
a
B
a'
m
b
40
140
D
60

Dielectric Polarization Effects in Insulators — the Berlin Prize Problem

Hertz now had the apparatus and techniques to tackle the Berlin Prize problem proposed to him by Helmholtz eight years earlier. The work is described in his paper "On electromagnetic effects produced by electrical disturbances in insulators"[20]. In the diagram of the apparatus the dimensions are in centimeters. In the center is an assembly of an oscillator and a circular detector (photograph). The oscillator dipole A-A' uses flat plates instead of spheres for loading. The detector loop B is mounted on a spindle so that it can rotate. At C is a metal sheet and at D is a wooden box for holding dielectric material.

Since the apparatus bears no resemblance to present-day apparatus and the experiments themselves are not easy to interpret, it seems best that the experiments be described in Hertz's own words:

> When the spark-gap f lies in the horizontal plane A A', i.e., at a or a', it is entirely free from sparks.

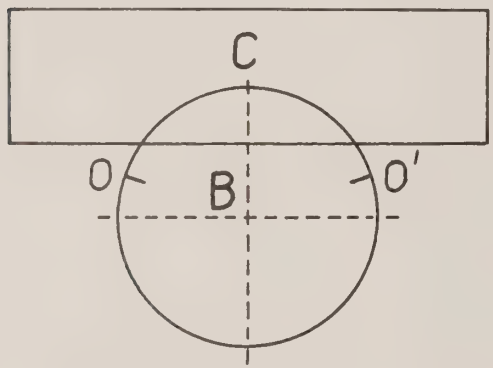


When the circle is rotated a few degrees in either direction from this position, minute sparks arise. These small sparks increase in length and strength as the spark gap is removed farther from the position of equilibrium and reach maximum length of about 3 mm when f is at the highest and lowest points, b and b' respectively, of the circle . . .

It will assist us in what follows if we also consider here the phenomena which occur when we shift the circle B a little downwards, parallel to itself and without moving it out of its plane. When this is done the sparking distance increases at the highest point and diminishes at the lowest point; the points which are free from sparks — the null-points as we may call them — no longer lie on the horizontal line through the axis, but appear to be rotated downwards through a certain angle on either side. . . .

Hitherto, it has been assumed that the conductors A A' and B are set in a large room as far away as possible from all objects which might disturb the action. Such an arrangement is necessary if we wish to secure an actual disappearance of the sparks at a and a'. . . . We have now to choose a conductor which will produce a moderately large effect, and of which we may assume the oscillation period to be smaller than that of our primary oscillation. These conditions are fulfilled by the conductor made of sheet metal, which is shown at C in our illustration.

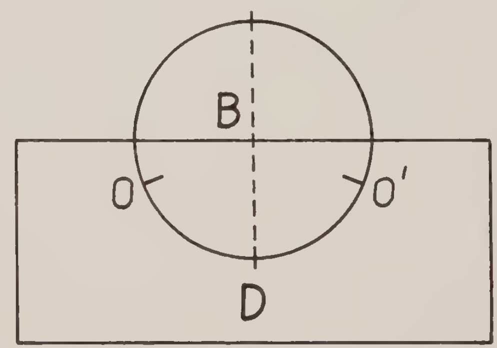
When it is lowered towards the primary conductor $A\ A'$, we observe the following effects: The spark length has decreased at the highest point b, and has increased at the lowest point b'; the null-points [o and o'] have moved upwards, i.e., towards the conductor C, whereas there is now noticeable sparking where the null-points originally were . . .



A very rough estimate shows that if large masses of insulating substances are brought near the apparatus, the quantities of electricity displaced by dielectric polarization must be at least as great as those which are set in motion by [conductors]. The approach of the latter has been found to produce a very noticeable effect in our apparatus; if, therefore, the approach of large insulating masses produced no similar effect, we should naturally conclude that the electricity displaced by dielectric polarization did not exert a corresponding electro-magnetic action. But if the views of Faraday and Maxwell are correct, we should expect that a noticeable effect would be produced, and further, that the approach of a non-conductor would act in the same way as that of a conductor having a very short period of oscillation. Experiment fully confirms this expectation; and the only difficulty in carrying out the experiments is that of procuring sufficiently large masses of insulating material.

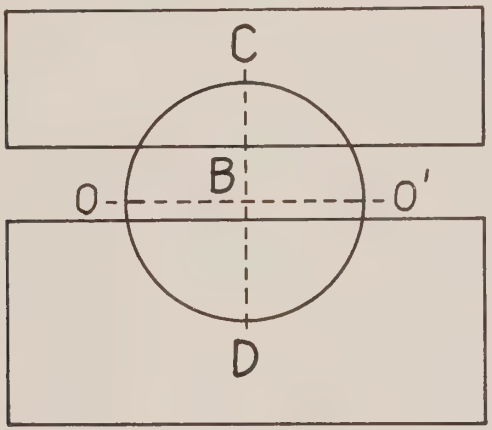
Hertz first experimented with a pile of books and observed expected effects. He next had a block of unmixed asphalt cast in the dimensions shown.

The apparatus was removed on to this [block of asphalt], the plates being laid upon the block. The effect could immediately be recognized. . . . The spark at the highest point of the circle was now considerably stronger than at the lowest point (that nearest the asphalt). The null-points were displaced downwards, i.e., towards the insulator, and when the plates were laid right upon it the angle of displacement (which could be measured with fair accuracy) was 23°. . . .



At the original zero-points there was now vigorous sparking. . . . If the apparatus was gradually removed in any direction away from the asphalt block the effect continually diminished, without experiencing any qualitative change. . . .

The accordance between the mode of action of the insulator and of a conductor is further shown by the fact that one can be compensated by the opposing action of the other. Thus, if the apparatus lay upon the asphalt, and the conductor C was brought near it from above, the null-points shifted backwards towards their original positions, and they again coincided with the points a and a′ when the conductor C was brought within about 11 cm of the conductor $A\ A'$. If the upper surface of the asphalt lay 5 cm beneath the plates A and A', compensation was attained as soon as C was brought within about 17 cm of $A\ A'$.



Wanting to be certain that impurities were not responsible for the observed effects, Hertz got a colleague to do an analysis. Indeed the asphalt did contain a large amount of mineral matter. Since the expense of undertaking further investigations on the same scale with pure substances was prohibitive, he had another transmitter, $A\ A$, and receiver, B, built to exactly one-half the linear dimensions. Hertz thus shifted from experimenting at approximately 6 meters wavelength (frequency 50 MHz) to 3 meters (frequency 100 MHz), which required blocks of dielectric material only one-eight the size in volume and weight. [Note: the existing original apparatus as well as the replicas at London and Chicago are of this smaller size.]

Hertz then investigated eight substances with the smaller apparatus. For asphalt the angle of rotation of the null-point was 31°. For artificial pitch obtained from coal it was 21°, but this artificial pitch contained not only hydrocarbons but also free carbon in a fine state of division, which would have some conductivity. Also, the asphalt ". . . was an excellent insulator [but] it contained . . . a large amount of mineral matter." The six other substances investigated were paper, dense dry wood, sandstone, sulfur, paraffin, and petroleum. The corresponding angles of rotation of the null-point were 8°, 10°, 20°, 13-14°, 7° and 7°, respectively.

Hertz noted:

> The concordance between the observations made upon so many substances, some of which were pure, scarcely leaves any doubt that the action is a real one, and that it must be attributed to the substances themselves, and not to impurities in them. . . . At present it does not appear possible to give any discussion of the quantitative relations of the experiments that would be of interest.

Hertz considered that his results had fulfilled the experimental goal of the Berlin Prize. He sent the manuscript to Helmholtz with a request: "Once again I am taking the liberty of sending you a paper with the respectful request to present it to the Academy[21], and if possible, to let it be printed in the proceedings. . . ."[22]. Presumably, Hertz did not collect the prize money, the time limit having expired in 1882. No one else had entered the contest. Perhaps he was the only individual besides Helmholtz who had given it any thought.

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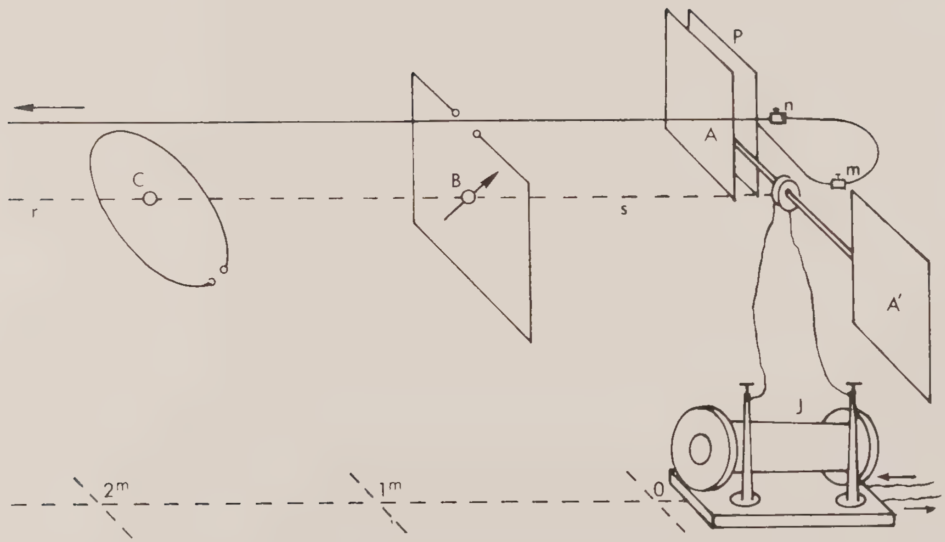
20. Hertz, *Electric Waves,* chap. 6.
21. The Prussian Academy of Science, Berlin.
22. Johanna Hertz, *Heinrich Hertz, Memoirs, Letters and Diaries,* Second Edition prepared by Mathilde Hertz and Charles Susskind, San Francisco Press, 1977, pp. 233-234.


P
n
m
A
C
B
r
s
A′
J
2m
1m
0

Guided Waves: Waves in Wire-Over-Ground-Plane Transmission Line

In the paper "On the finite velocity of propagation of electromagnetic actions"[23], Hertz describes his first experiment to measure the velocity of propagation of electromagnetic waves. The signal source is a variation on the Hertzian 6 m oscillator/radiator transmitter. Square plates *A A*′ are used for loading. The induction coil is shown below the transmitter. The transmission line is of wire-over-ground-plane construction, with the wire 1.5 m above the floor. The polarization is horizontal. Plate *P*, acting as a capacitor, keeps the high-voltage pulses off the transmission line. With the transmission line open-ended on the left, reflected waves interfere with incident waves and standing waves result. As one moves the detector along the line, the distance between nulls is one-half wavelength. Hertz obtained 2.8 m for the half-wavelength. According to Maxwell's theory, and as we know to be true, the product of frequency and wavelength gives the velocity of propagation, in this case the velocity of light in air.

Hertz had two objectives: (1) to demonstrate a finite velocity of propagation, a major distinction between Maxwell's theory and older theories, and (2) determine the velocity and compare it with Maxwell's prediction of 3×10^8 m per second. Hertz calculated the frequency of his source from an estimate of the capacitance and the inductance of the dipole resonator[24]. For the velocity, the product of wavelength × frequency, he arrived at 2×10^8 meters per second, not knowing of a computational error of 1/(2)½ for the frequency. Without the error his result for the velocity would have been 2.8×10^8 — within 7% of the correct value, a truly remarkable achievement. Hertz thus had clearly succeeded in his first objective, and did not know how truly successful he had been on the second. He published promptly, and the error in computation was later pointed out to him in a letter[25] from H. Poincare in France.

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23. Hertz, *Electric Waves*, Chap. 7.
24. Hertz, *Electric Waves*, Chap. 2, pp. 50 and 51.
25. Letter from Poincare to Hertz, September or October 1890, the Deutsches Museum, #3001.

Skin Effect and Guided Waves — Coaxial Transmission Line

Maxwell explicitly suggested the phenomenon of *skin effect*, the tendency of high-frequency alternating currents and magnetic flux to penetrate the surface of a conductor only to a limited depth. As frequency is increased, RF currents penetrate conductors to a smaller and smaller depth, so that finally most of the energy of waves travels in the space outside and between conductors.

To investigate, Hertz conducted experiments by completely enclosing his detector in a box of thin metallic sheets of various thicknesses estimated to be no more than 1/20 mm, and observed complete shielding. Using the same sheet material to form the outer conductor of a coaxial line, similar shielding was obtained. For an even thinner outer conductor, glass tubes that had been chemically silvered were used as the outer conductor. Electromagnetic energy only appeared in his external detector "when the film of silver was so thin it was no longer quite opaque to light, and certainly was thinner than 1/1000 mm."[26]

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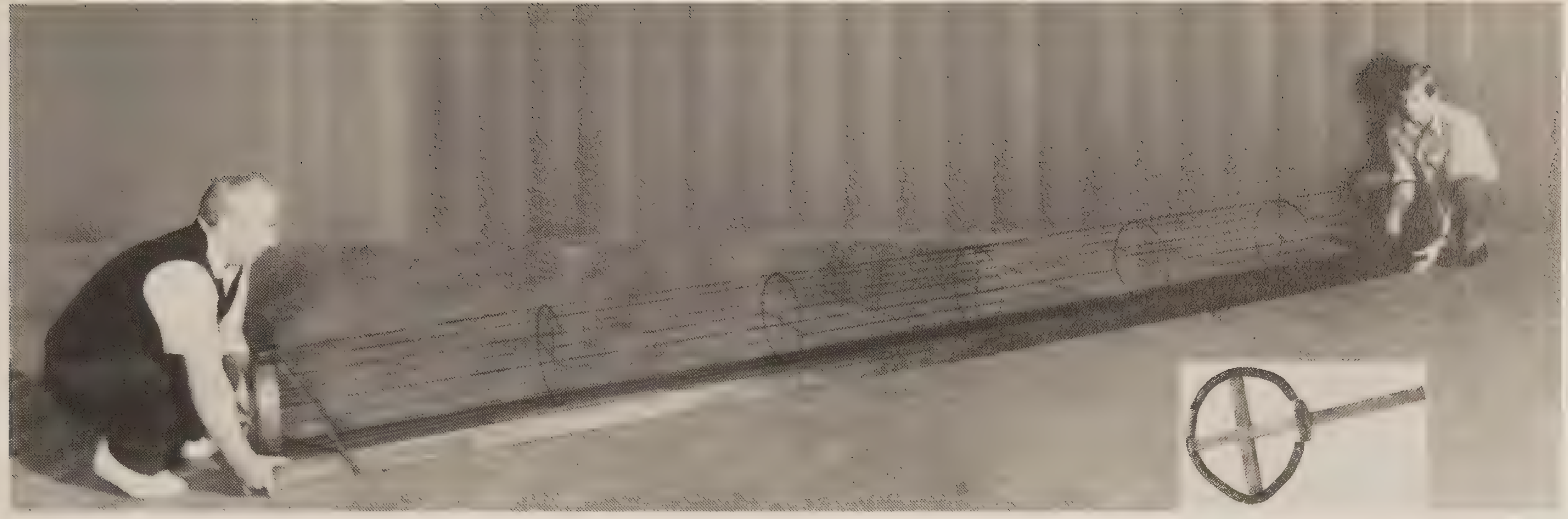
26. Hertz, *Electric Waves,* Chap. 10.



Hertz wanted to conduct experiments in a uniform transmission line, free of interfering obstacles. He stated:

> If our waves have their seat in the space surrounding [conductors], then a wave gliding along a single wire will not be propagated through the air alone; but, inasmuch as its action extends to a considerable distance, it will be propagated in the neighboring walls, the floor, etc., and will develop into a complicated phenomenon . . . We can thus take measures to secure that propagation occurs only through air or another insulator . . .[27].

A coaxial transmission line section 5 m (17 ft.) long and 30 cm (1.2 ft) in diameter was built. The outer conductor is not made of solid metal, since that would have made the interior of the line inaccessible. It is built up of 24 copper wires stretched parallel to one another along the generating surface of seven equidistant circular rings of stout wire. At the center of each large ring is a small ring supported by spokes of cotton cord. Running a wire through the center rings yielded a coaxial transmission-line section. A preliminary experiment had shown that the parallel wires were close enough together to provide screening. The wavelength of the signal source used was 6 m (frequency 50 MHz).

The resonant circuit for the small receiver/detector for use inside the coaxial line consists of about 125 turns of 1 mm copper wire wound in a tight heliz 1 cm in diameter, pulled out a little, and bent into a circle of 12 cm in diameter. "Special experiments had shown that this circle was in resonance with the waves of 3 meters* length in the wire, yet it was sufficiently small to be introduced between the central wire and the tube."

This detector could be inserted between the outer wires, positioned, and moved along the line to measure the fields inside the line. It was thus the first slotted line. With it Hertz demonstrated standing waves, with nodes half a wavelength from a short circuit and a quarter wavelength from an open circuit. He also showed that the wavelength inside the line was the same as a corresponding wave in free space, with the same dielectric (in this case air). The first practical use of coaxial line came more than four decades later, in the early 1930s.

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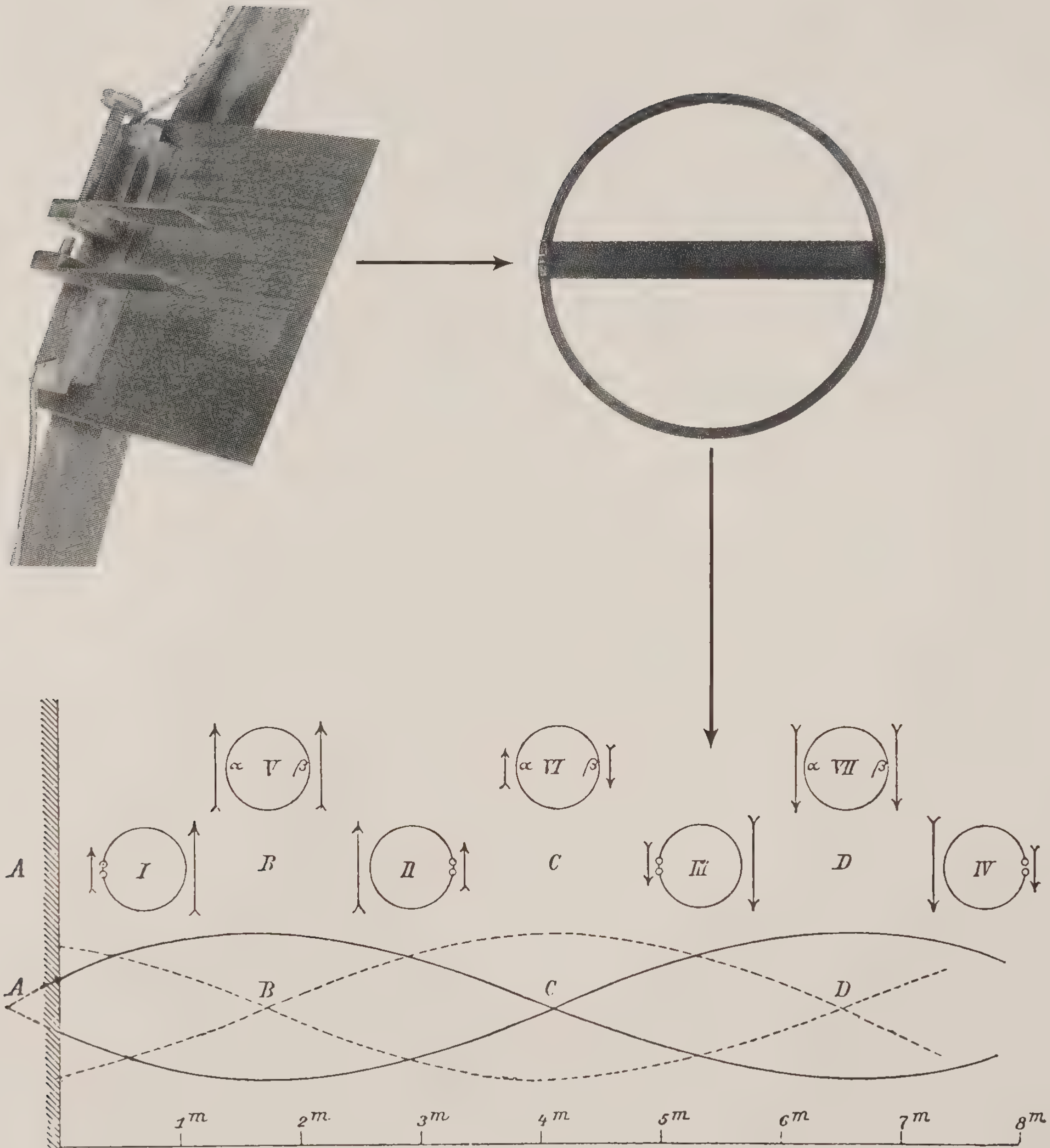
27. Hertz, *Electric Waves,* p. 167.

* Actually, 6 meters. Hertz often quoted half wavelength for the wavelength.


α V β
α VI β
α VII β
A
I
B
II
C
III
D
IV
A
B
C
D
1 m
2 m.
3 m
4 m
5 m
6 m
7 m
8 m

Electromagnetic Waves in Air and Their Reflection[28]

The transmitter is on the right, (photograph) with polarization vertical. The center of the transmitter was 2.5 m from the floor. On the left (cross-section), is a sheet of metal used as a reflector. Waves reflected back toward the transmitter interfere with incident waves and create standing waves. The solid lines denote voltage standing waves. Hertz visualized the dotted lines as magnetic standing waves.

> The physics lecture room in which these experiments were carried out is about 15 meters long, 14 meters broad, and 6 meters high. Parallel to the two longer walls there are two rows of iron pillars, each of which rows behaves much like a solid wall towards the electromagnetic action, so that the parts of the room which lie outside these cannot be taken into consideration. Thus only the central space, 15 meters long, 8.5 meters broad, and 6 meters high, remained for the purpose of experiment. From this space I had the hanging parts of the gas pipes and the chandeliers removed so that it contained nothing except wooden tables and benches which could not be removed. No objectionable effects were to be feared from these, and none were observed. The front wall of the room, from which the reflection was to take place, was a massive sandstone wall in which were two doorways, and a good many gas-pipes extended into it. In order to give the wall more of the nature of a conducting surface a sheet of zinc 4 meters high and 2 meters broad was fastened on to it. . . .

The circles denote positions where Hertz used a receiver of circular configuration (upper photographs) to measure the amplitude of the voltage standing waves. In use, the receiver was mounted so that it could be rotated about its axis. Note the two small plates soldered to the loop on each side of the spark gap detector, presumably for tuning the receiver to transmitter frequency. At position *I*, by rotating the receiver to two horizontal positions 180° apart, he noted decreasing amplitude toward the reflector. At *II* and *IV* he noted decreasing amplitude toward null points, and at *III* increasing amplitude away from a null. At *V* and *VII* there was equal amplitude on each side of an antinode, and at *VI* there was equal amplitude on each side of a null. The distance between nulls was reckoned to be one-half wavelength.

Hertz projected a voltage null beyond the reflector, not in the plane of the reflecting surface as expected. He reasoned that this might be due to the finite conductivity of the metal. We now know that that is not too likely. Since the length of his reflector was less than two wavelengths, it must have been refraction.

That was not Hertz's main problem, however. He got a measured wavelength that was too long, so that the product of wavelength and calculated frequency gave too great a velocity. His measured value for the half-wavelength was 4.8 m, compared to 2.8 m for the wire-over-ground-plane transmission line and 3 m for the coaxial line. The problem was probably due to waveguide effects: reflections from the floor, the iron columns in the lecture room, or from an iron stove located near the propagation path. Hertz published promptly, however, warts and all, as was his practice. He was obliged to observe that the velocity in air appeared to be different than on wires. He noted that since they were both finite, his results could still be in keeping with Maxwell's theory.

In any case, the experiment was replicated by Edouard Sarasin and Lucien de la Rive in Switzerland[29], and they confirmed that indeed the velocities were the same. In later experiments (p. 38), using a shorter wavelength, Hertz also got the correct result.

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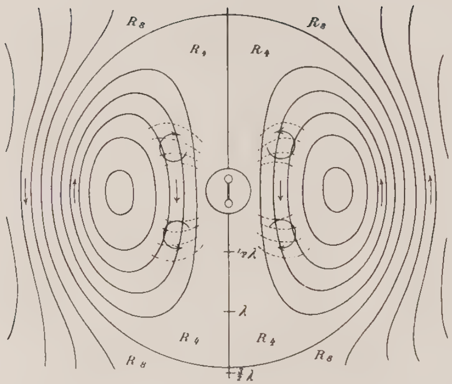
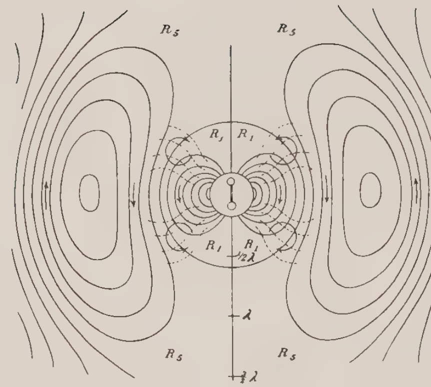
28. Hertz, *Electric Waves,* Chap. 8.
29. *Electric Waves,* p. 12.

t = 0



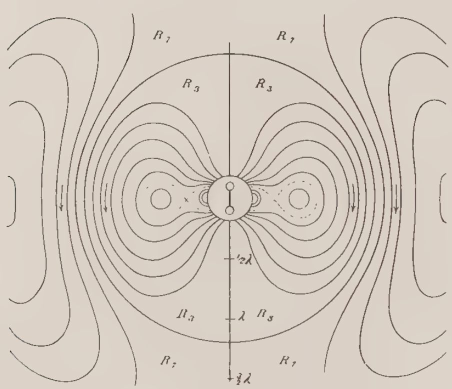
R8
R8
R4
R4
½λ
λ
R4
R4
R8
R8
3/2λ

¼T



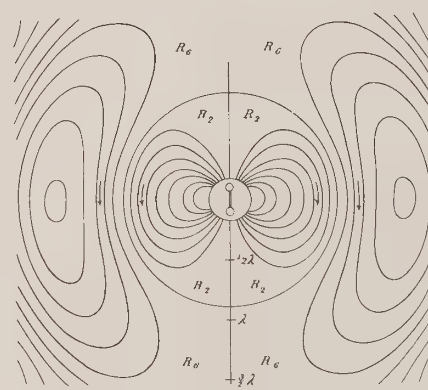
R5
R5
R1
R1
R1
R1
½λ
λ
R5
R5
3/2λ

¾T



R7
R7
R3
R3
½λ
R3
λ
R3
R7
R7
3/2λ

½T



R6
R6
R2
R2
½λ
R2
R2
λ
R6
R6
3/2λ

The Fields From a Dipole Antenna

Hertz interspersed his experiments with analytical work. In his paper "The forces of electric oscillations treated according to Maxwell's theory"[30], Hertz explained:

> The results of the experiments on rapid oscillations which I have carried out appear to me to confer upon Maxwell's theory a position of superiority to all others. Nevertheless, I based my first interpretation of these experiments upon the older views, seeking partly to explain the phenomena as resulting from the cooperation of electrostatic and electromagnetic forces. To Maxwell's theory in its pure development such a distinction is foreign. Hence, I wish now to show that the phenomena can be explained in terms of Maxwell's theory without introducing this distinction. Should this attempt succeed, it will at the same time settle any question as to a separate propagation of electrostatic force, which indeed is meaningless in Maxwell's theory. Apart from this special aim, a closer insight into the play of forces which accompany a rectilinear oscillation is not without interest.

Hertz's illustration of his calculations of the development of fields around an oscillating electric dipole (very short dipole antenna) is shown at left for each quarter cycle, or, by suitable reversal of the arrows, for all subsequent times which are whole multiples of one quarter period. A portion of each of the outer lines of force detaches itself as a self-closed line of force which advances independently into space, while the remainder of the lines of force sink back into the oscillating dipole. This loss of energy corresponds to radiation into space. At a large distance the fields become entirely transverse.

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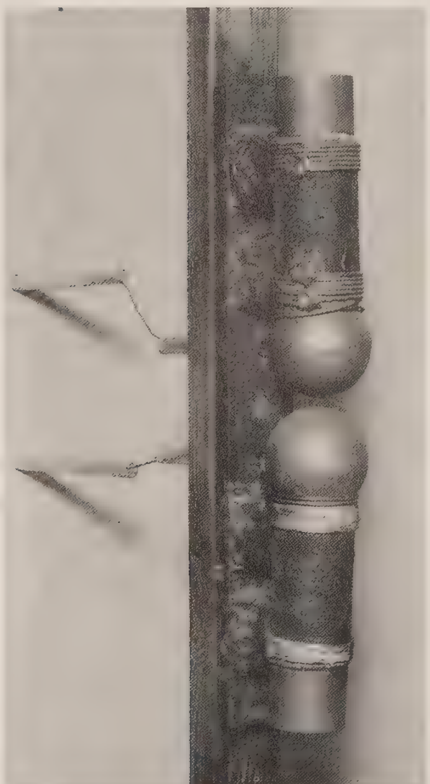
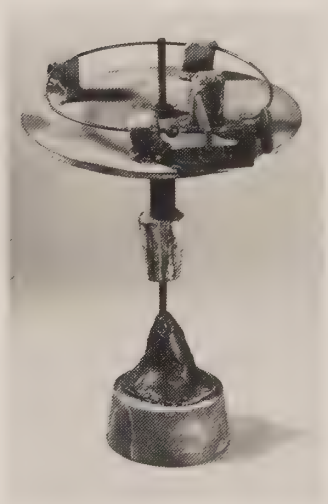
30. Hertz, *Electric Waves,* Chap. 9.

Shorter Wavelength Apparatus





Hertz had previously tried his large 6 m wavelength transmitter in front of a cylindrical parabolic reflector, but obtained no focusing[31]. He realized that the reflector was much too small in terms of wavelength. Rather than build a larger reflector, which would have required him to go outside the building, he scaled his signal source and detector to a shorter wavelength, of about 60 cm (500 MHz frequency). The resonant circuit of the transmitter is again a half-wavelength dipole. The cylindrical brass body, 3 cm diameter and 26 cm long, is interrupted in the center with spheres 4 cm diameter to act as the switch.

The resonant circuit of the receiver is a circular loop, scaled to 7.5 cm diameter so as to resonate with the oscillator.

With the shorter wavelength waves Hertz repeated previous experiments. One result was finding that "these short waves traveled along wires at very nearly the same velocity as in air"[32]. He then went on to conduct focused-beam experiments to demonstrate the optics-like properties of waves at metric wavelengths.

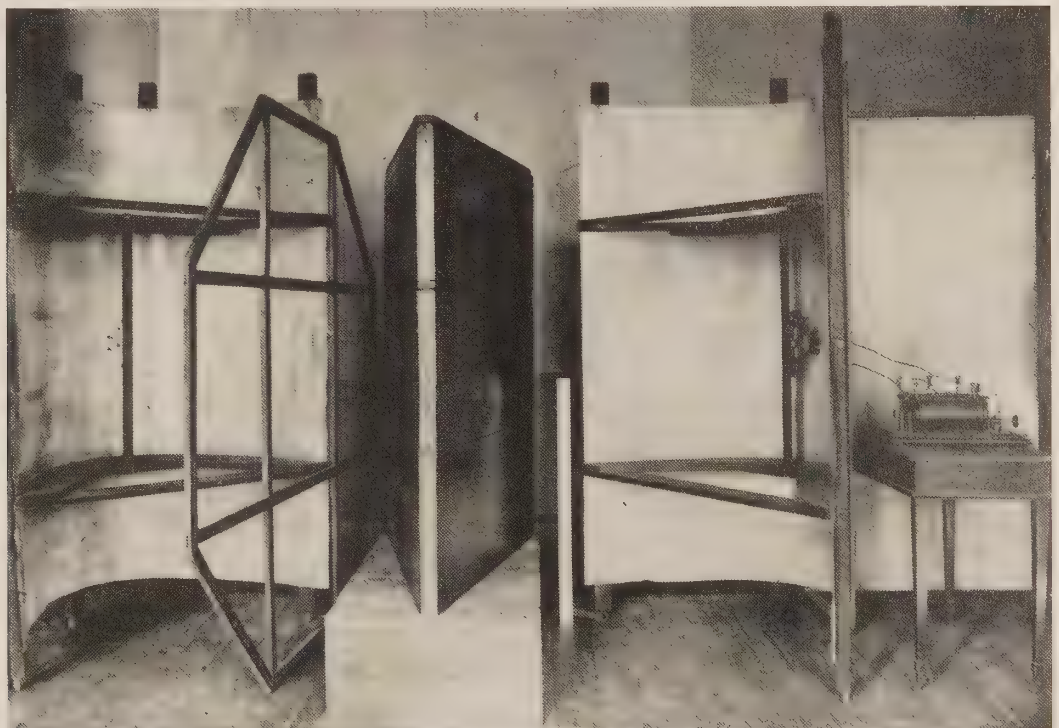
31. Hertz, *Electric Waves,* p. 172.
32. Hertz, *Electric Waves,* p. 17, see also pp. 175 and 176.

The 60 cm Apparatus

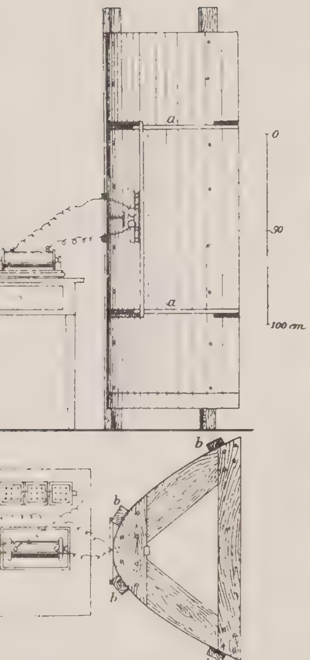
The photograph shows Hertz's apparatus used for focused-beam experiments to demonstrate the optics-like properties of electric waves of about 60 cm wavelength. It was taken in Hertz's Physical Institute in Karlsruhe, around 1888[33]. Shown left-to-right are the receiver/detector with cylindrical parabolic reflector, a wooden frame with parallel wires for polarization experiments, a stack of three wedge-shaped wooden boxes to hold dielectric materials for refraction experiments, an oscillator/transmitter with cylindrical parabolic reflector, and the transmitter power supply (on the table). The two output leads from the induction coil on the table pass through glass tubes in holes in the back of the reflector, and are attached to the transmitter dipole. This induction coil appears to have an adjustable vibrator/current interrupter mounted on the end at the right. A wire from it may be seen that (presumably) goes to a battery located behind the induction coil. The table is on casters, and therefore can be moved around with the transmitter to the desired position for use. The plane metal reflector is standing behind the table.

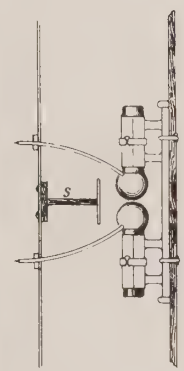
In addition to the text on the following four pages, see pages 44 and 45 for Hertz's description of experiments using this apparatus, along with his interpretation of the results and their meaning.

33. August Schleiermacher, *op. cit.*



Focused-Beam Experiments





With the apparatus operating at shorter wavelength and after getting good results, Hertz started a new phase of investigation, described in his paper "On electric radiation[34]." His purpose was to show the similarity in characteristics of electromagnetic waves at metric wavelengths to that of light at wavelengths a million times shorter. The story is better told in Hertz's words:

> As soon as I had succeeded in proving that the action of an electric oscillation spreads out as a wave into space, I planned experiments with the object of concentrating this action and making it perceptible at greater distances by putting the primary conductor in the focal line of a large concave parabolic mirror. These experiments did not lead to the desired result, and I felt that the want of success was a necessary consequence of the disproportion between the length . . . of the waves [wavelength] used and the [largest] dimensions which I was able . . . to give to the mirror. Recently I have observed that the experiments which I have described can be carried out quite well with oscillations of more than ten times the frequency, . . . less than one-tenth the [wavelength] of those which were first discovered. I have, therefore, returned to the use of concave mirrors, and have obtained better results than I had ventured to hope for. I have succeeded in producing distinct rays of electric force, and in carrying out with them the elementary experiments which are commonly performed with light and radiant heat.

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34. Hertz, *Electric Waves,* Chap. 11.

Transmitter (left)
Hertz placed the transmitter half-wave dipole in the focal line of a parabolic cylinder reflector. The focal length was 12.5 cm. The reflector is made from a sheet of zinc 2 m long and 2 m wide bent over a wooden frame of the desired curvature. The resulting reflector is 2 m high and 1.2 m wide at the aperture, and its depth is 0.7 m. The high-voltage pulses from the induction coil are brought through by leads from the back.

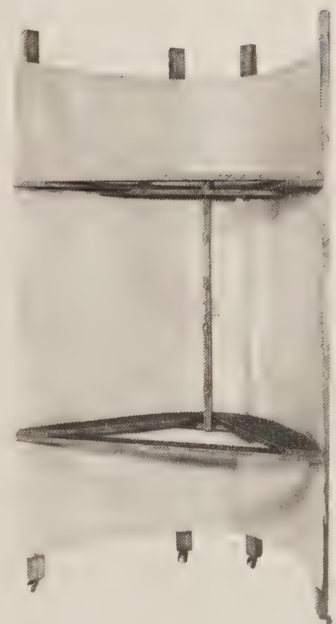
Receiver (right)
Hertz used a similar reflector for the receiver, and, for the first time, made use of a dipole as the resonant element in his receiver:

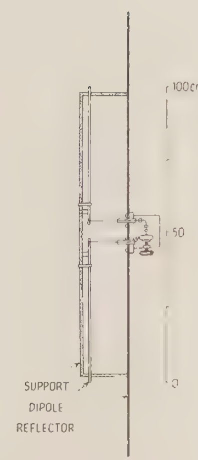
> The circular conductor gives only a differential effect, and is not adapted for use in the focal line of a concave mirror. Most of the work was therefore done with another conductor arranged as follows. Two straight pieces of wire, each 50 cm long and 5 mm in diameter, were adjusted in a straight line so that their near ends were 5 cm apart.

This receiver dipole made of thin wire and with an overall length of 105 cm, is about 3/2 wavelengths long.

The receiving dipole is mounted in the focal line of the reflector. Behind, fed by a short length of parallel wire transmission line, is his adjustable spark gap detector.

Rectilinear propagation
The transmitter and receiver units are on casters. If they are aimed toward each other, the maximum signal is obtained. If a sheet of metal is interposed there is no signal. Placing them side by side and aiming them both in the same direction likewise yields no signal.

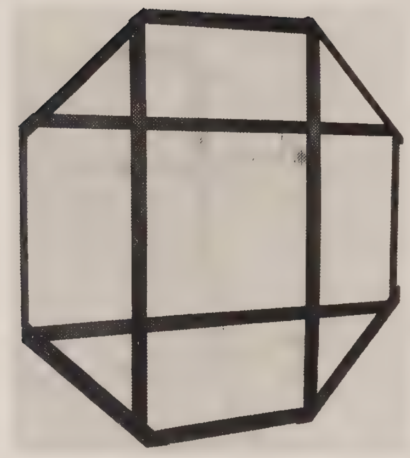


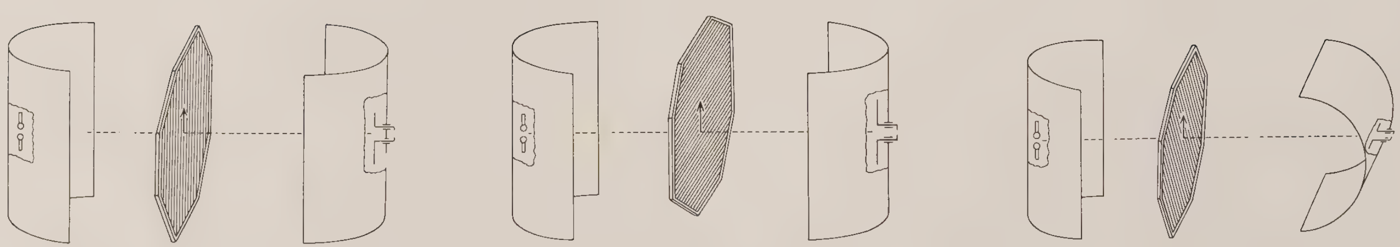


RECEIVER DIPOLE AND SPARK GAP DETECTOR

Polarization

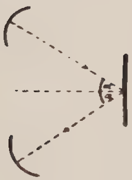
A wooden frame with parallel wires was built to demonstrate polarization effects. When the wires are placed in the plane of polarization between the transmitter and receiver, the signal is cut off, but when the wires are at right angles the signal is transmitted. Note that Hertz made the frame octagonal. He showed that when the wires are set at 45 ° to the plane of polarization, the wave is resolved into two components — one horizontal and one vertical. Thus even if the receiver is turned at right angles to the transmitter, half of the signal power is transmitted.

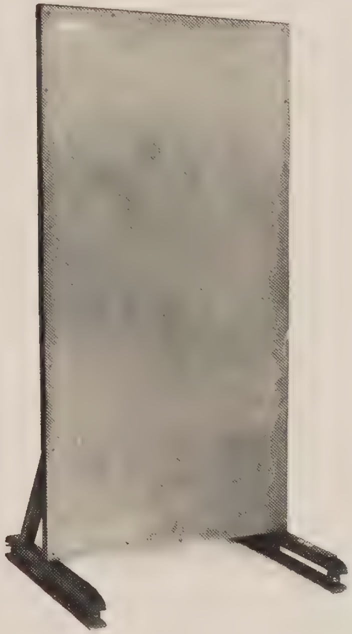




Reflection

When the units are aimed at a reflecting surface made of sheet metal as illustrated, the angle of reflection is equal to the angle of incidence, as in optics. Hertz referred to this type of conducting surface as being electrically isotropic, since it conducts current equally in all directions on the surface.



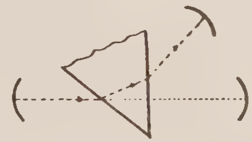


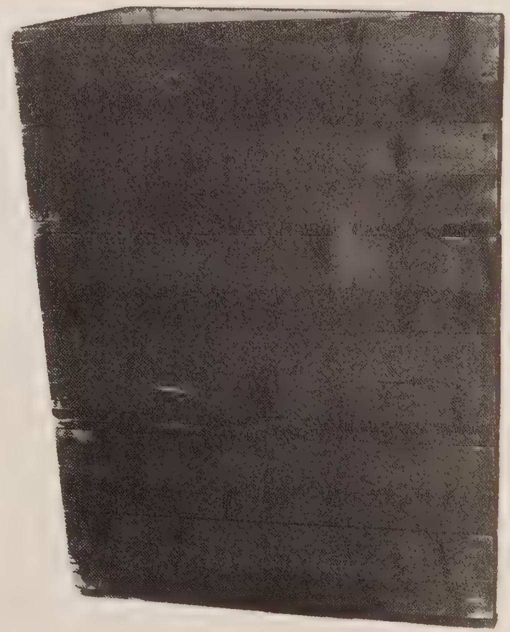
Reflection from an Electrically Anisotropic Surface

When the plane metal reflector is replaced with the frame of parallel wires, reflection is observed when the wires are in the plane of polarization, but there is no reflection when the wires are at right angles. With the wires placed at 45° to the plane of polarization, the signal is observed in the receiver detector both when the receiver is in the plane of polarization and when it is at right angles to it, because the wave is resolved into two components, one vertical and one horizontal. Hertz referred to the array of parallel wires as being equivalent to an electrically eolotropic (anisotropic) surface.

Refraction

A stack of three wedge-shaped forms was built which could be filled with dielectric material such as tar (pitch). From the angle of refraction and the angle of the wedge, Hertz could calculate the index of refraction, the square of which is the relative dielectric constant (or permittivity) for a homogeneous, isotropic material. This was the first dielectric-constant measurement at microwave wavelengths.





On the Relations Between Light and Electricity

On 20 September 1889, five months after he moved to Bonn, Hertz delivered a lecture on the above subject at the Natural Scientists' meeting in Heidelberg[35]. He reviewed the history of light, and of electricity and magnetism, and reviewed the development of a theory of electromagnetism by Faraday and Maxwell. He then commented on his own experiments, their significance, and his anticipation of the future.

"All these experiments in themselves are very simple, but they lead to conclusions of the highest importance. They are fatal to any and every theory which assumes that electric force acts across space independently of time. They mark a brilliant victory for Maxwell's theory. No longer does this connect together natural phenomena far removed from each other. Even those who used to feel that this conception as to the nature of light had but a faint air of probability now find a difficulty in resisting it. In this sense we have reached our goal. But at this point we may perhaps be able to do without the theory altogether. The scene of our experiments was laid at the summit of the pass which, according to the theory, connects the domain of optics with that of electricity. It is natural to go a few steps further, and to attempt the descent into the known region of optics. There may be some advantage in putting theory aside. There are many lovers of science who are curious as to the nature of light and are interested in simple experiments, but to whom Maxwell's theory is a seven-sealed book. The economy of science, too, requires of us that we should avoid roundabout ways when a straight path is possible. If with the aid of our electric waves we can directly exhibit the phenomena of light, we shall need no theory as interpreter; the experiments themselves will clearly demonstrate the relationship between the two things. As a matter of fact such experiments can be performed. We set up the conductor in which the oscillations are excited in the focal line of a very large concave mirror. The waves are thus kept together and proceed from the mirror as a perfect parallel beam. We cannot indeed see this beam directly, or feel it; its effects are manifested in exciting sparks in the conductors upon which it impinges. It only becomes visible to our eyes when they are armed with our resonators [receivers]. But in other respects it is really a beam of light. By rotating the mirror we can send it in various directions, and by examining the path which it follows we can prove that it travels in a straight line. If we place a conducting body in its path, we find that the beam does not pass through — it throws shadows. In doing this we do not extinguish the beam but only throw it back: we can follow the reflected beam and convince ourselves that the laws of reflection are the same as those of the reflection of light. We can also refract the beam in the same way as light. In order to refract a beam of light we send it through a prism, and it then suffers a deviation from its straight path. In the present case we proceed in the same way and obtain the same result; excepting that the dimensions of the waves and the beam make it necessary for us to use a very large prism. For this reason we make our prism of a cheap material, such as pitch or of asphalt. Lastly, we can with our beam observe those phenomena which hitherto have never been observed excepting with beams of light — the phenomena of polarization. By interposing a suitable wire grating in the path of the beam we can extinguish or excite the sparks in our resonator in accordance with just the same laws as those which govern the brightening or darkening of the field of view in a polarizing apparatus when we interpose a crystalline plate.

Thus far the experiments. In carrying them out we are decidedly working in the region of optics. In planning the experiments, in describing them, we no longer think electrically, but optically. We no longer see currents flowing in the conductors and electricities accumulating upon them: we only see waves in the air, see how they intersect and die out and unite together, how they strengthen and weaken each other. Starting with purely electrical phenomena we have gone on step by step until we find ourselves in the region of purely optical phenomena. We have crossed the summit of the pass: our path is downwards and soon begins to get level again. The connection between light and electricity, of which there were hints and suspicions and even predictions in the theory, is now established: it is accessible to the senses and intelligible to the understanding. From the highest point to which we have climbed, from the very summit of the pass, we can better survey both regions. They are more extensive than we had ever before thought. Optics is no longer restricted to minute ether waves a small fraction of a millimeter in length; its domain is extended to waves which are measured in decimeters, meters, and kilometers. And in spite of this extension it merely appears, when examined from this point of view, as a small appendage to the great domain of electricity. We see that this latter has become a mighty kingdom. We perceive electricity in a thousand places where we had no proof of its existence before. In every frame, in every luminous particle we see an electrical process. Even if a body is not luminous, provided it radiates heat, it is the center of electric disturbances. Thus the domain of electricity extends over the whole of nature. It even affects ourselves closely: we perceive that we actually possess an electrical organ — the eye. These are the things that we see when we look downwards from the high standpoint. Not less attractive is the view when we look upwards towards the lofty peaks, the highest pinnacles of science. We are at once confronted with the question of direct actions-at-a-distance. Are there such? Of the many in which we believed there now remains but one — gravitation. Is this too a deception? The law according to which it acts makes us suspicious. In another direction looms the question of the nature of electricity. Viewed from this standpoint it is somewhat concealed behind the more definite question of the nature of electric and magnetic forces in space. Directly connected with these is the great problem of the nature and properties of the ether which fills space, of its structure, of its rest or motion, of its finite or infinite extent. More and more we feel that this is the all-important problem, and that the solution of it will not only reveal to us the nature of what used to be called imponderables, but also the nature of matter itself and of its most essential properties — weight and inertia. The quintessence of ancient systems of physical science is preserved for us in the assertion that all things have been fashioned out of fire and water. Just at present physics is more inclined to ask whether all things have been fashioned out of the ether? These are the ultimate problems of physical science, the icy summits of its loftiest range. Shall we ever be permitted to set forth on one of these summits? Will it be soon? Or have we long to wait? We know not: but we have found a starting-point for further attempts which is a stage higher than any used before. Here the path does not end abruptly in a rocky wall; the first steps that we can see form a gentle ascent, and amongst the rocks there are tracks leading upwards. There is no lack of eager and practiced explorers: how can we feel otherwise than hopeful of the success of future attempts?"

When this lecture was given, Hertz was in fact engaged in an investigation which he hoped might *experimentally* decided for or against the concept of action-at-a-distance (next page).

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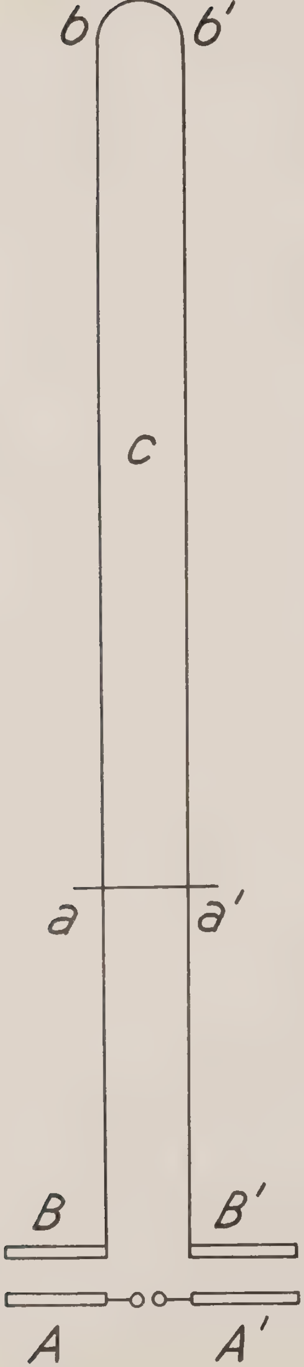
35. Hertz, *Miscellaneous Papers,* Chap. 20.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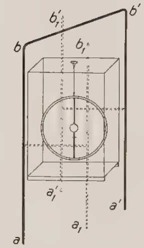

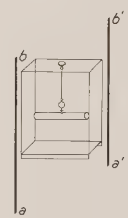
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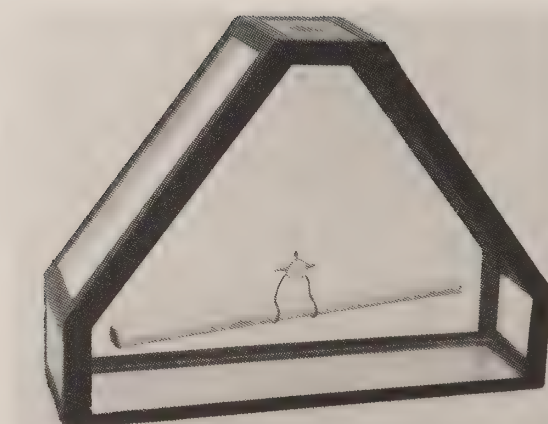

The Mechanical Action of Electric Waves

Attempts to Measure the Strength and Distribution of Electromagnetic Fields

In his October 1889 lecture on Light and Electricity (pp. 44 and 45) Hertz revealed that he endorsed Maxwell's theory as he interpreted it. He admitted to not being at ease with some of the concepts, or with the ether model.

In his last experiments in electromagnetics, (started in Karlsruhe and completed in Bonn), described in his paper "On the mechanical action of electric waves on wires"[36], Hertz succeeded in experimentally giving further elucidation to the nature of electromagnetic waves. He stated:

> The investigation of the mechanical [pondermotive] forces to which a conductor is subjected under the action of a series of electric waves appeared to me to be desirable for several reasons. (1) In the first place, these forces might supply means of investigating such waves quantitatively . . . (2) In the second place, by examining the nature and distribution of the mechanical forces, I hoped to find a means of demonstrating the existence of the magnetic force in addition to the electric force. Only the latter has manifested itself in the observations hitherto made . . . (3) In the third and last place — and this was more especially the object of the investigation — I hoped to be able to devise some way of making observations on waves in free air, that is to say, in such a manner that any disturbances which might be observed could in no way be referred to any action-at-a-distance. This last hope was frustrated by the feebleness of the effects produced under the circumstances. I had to content myself with examining the effects produced by waves traveling along wires, although in so doing the most important object of the experiments was missed . . . waves in wires cannot be made use of to decide between the older and the newer views [of electromagnetics].

Thus the lack of sensitivity of his instruments prevented Hertz from achieving his third objective. Apparently he did not attempt to calibrate his apparatus for quantitative measurements (first objective) which would have been of interest to him only if he could have measured the fields in free space, his third objective.

Hertz did achieve his second objective, and thus further clarified the nature of electromagnetic waves.

Hertz's instrument for measuring the mechanical action of the electric force made use of a small tube 5.5 cm long and 0.7 cm in diameter made of rolled-up gilt paper, suspended by a silk thread with its axis horizontal (schematic and photograph). A very small magnet gave the tube a definite position of rest, and a deviation from the position was measured by means of a small mirror. The whole system was mounted in a glass case. This has been called a rolled-paper galvanometer. By this time, starting in 1889, he was able to make some use of contributions by other investigators who were already working in the new field of electromagnetics which he had opened up. He found that a two-wire transmission line (schematic) of the type which was being used by Ernst Lecher (hence the term Lecher line) at the University of Vienna produced fields strong enough to be measured. The signal source was a 6 m wavelength oscillator. Placed between the wires, with signal present, the force on the tube tends to make it line up with the plane of the wires. Hertz found minimum deflection at nodal positions $a\ a'$ and $b\ b'$, and maximum deflection at position c in between.

To investigate the magnetic force, use was made of a circular loop of aluminum wire 6.5 cm diameter suspended by a silk thread, with a magnet to give a definite position of rest and a mirror to indicate a deviation from that position. This assembly was enclosed in a glass case (schematic). Hertz noted deflection of the same magnitude as for the electric force detector. He noted maxima at positions $a\ a'$ and $b\ b'$, and found the direction of the magnetic force to be perpendicular to that of the electric force, as he had expected.

36. *Electric Waves*, Chap. 12.

The Legacy of Hertz

Hertz's work in electromagnetics opened up the RF portion of the electromagnetic spectrum between DC and light for scientific and practical uses, and started a new line of investigation in the ultraviolet. This book has been concerned with the work of Hertz as reported in papers listed on p. 50, all except one reprinted in Vol. II of his collected works, *Electric Waves*.

Although Hertz is best known for his work in electromagnetics, analytical and especially experimental, this work accounts for less than one half of his career output. His interests were broad, with work in mechanics, instrumentation, friction, magnetics, meterology, electricity, cathode rays, and electrical discharge in gases, much of which is covered in articles reprinted in vol. I of his collected works, *Miscellaneous Papers*.

Hertz's work and his outlook was that of pure science. Patents or products were not in his thinking, yet the results of his work form the basis for a wide range of products and services represented in diverse industries and institutions today.

Because Hertz's life was cut short, he did not establish a "school" of students who could carry on his work. During the time in Karlsruhe he taught small classes of undergraduates, including a class in meterology that all forestry students were required to take. He had one junior faculty colleague, Dr. August Schleiermacher, with whom he shared teaching. In his research he worked alone with the help of a small staff in the Physical Insititute. Seemingly there was no one at Karlsruhe, faculty or student, who could really benefit from Hertz's great skill for building a basic apparatus that worked, or his outstanding ability in experimentation, a legacy of the teaching of Helmholtz and others at the University of Berlin.

When he moved to the University of Bonn in April 1889, his field for activity opened up in a university with graduate research and teaching. His fame had started to spread, with the result that advanced students began to apply to study under him. Most of his time in Bonn, between bouts with illness, was taken up with organizing, refurbishing, and equipping the laboratories. An operation on 23 September 1893 revealed "an extremely old and therefore very stubborn" tooth abcess that had bothered him for years and had become increasingly distractive.

At Bonn Hertz did fulfill a long-time interest by writing a book on mechanics from a unique point of view. His assistant Philipp Lenard completed the book, *The Principles of Mechanics, Presented in a New Form*, and had it published after Hertz's untimely death on 1 January 1894, a few months before his 37th birthday. He was a victim of an illness (blood poisoning from the infection of his jaw) that would be treated routinely with medication today.

At the University of Bonn, Hertz completed his last experiments in electromagnetics (pp. 46 and 47). He also started a new line of research which quickly bore fruit: sending a beam of cathode rays against a thin metal target and observing its passage through the target.

Unfinished

The last two chapters of *Electric Waves* have no technical significance today, but are of scientific interest. In Chapter 13, "On the fundamental equations of electromagnetics for bodies at rest" (1890), Hertz formulated Maxwell's equations in the compact form that rapidly achieved widespread influence and has been standard ever since. Heaviside had also formulated the equations, but it was Hertz's work that spread the equations through the physics community.

In Chapter 14 of *Electric Waves*, "On the fundamental equations of electromagnetics for bodies in motion" (1890), Hertz was on the

track of one of the most fundamental concepts in the history of science — the special theory of relativity. In a letter to Heaviside of 3 September, 1889 from Bonn, Hertz states:

> The motion of the ether relatively to matter — this is indeed a great mystery. I thought about it often but did not get an inch of advance. I hope for experimental help; all that has been done till now has given negative results. . . . Take a copper sphere rotating in a homogeneous magnetic field. You cannot treat the case without having recourse to action at a distance. Maxwell's solution is by action at a distance. And I do not see how it could be otherwise before we know if the ether turns round with the sphere or is at rest, or where is the frontier between the moving and the resting ether. . . . As to the structure of the ether, . . . the structure of all the models imagined until now is certainly not the structure of the ether; in these points I am absolutely of your opinion[37].

Hertz, like most physicists of the day, assumed that electric and magnetic fields moved along unchanged with the matter that carried them. This assumption has a fundamental flaw, as Einstein was to discover 15 years later, including the fact that the concept of an ether is not necessary. Knowledge of the fields is enough so long as account is taken of the fact that the velocity of light is constant in all coordinate systems, moving or not. But this knowledge was not available in 1890.

The paper, "On an effect of ultraviolet light upon the electrical discharge" (1887) has been discussed in this book. It started a new line of investigation in physics, and was the start of quantum physics. On the practical side, Elster and Gietel in Germany produced the first photocell two years later.

In the work described in the paper, "On experiments on the cathode discharge" (1883), Chapter 13 in *Miscellaneous Papers*, Hertz was a victim of inadequate technology. He tried to deflect cathode rays using an electric field between two plates, but the potential difference resulted in a gas discharge breakdown in the poor vacuum. No deflection was obtained, which made it appear that the cathode rays did not have a charge. J.J. Thomson repeated the experiment 12 years later, and on applying the voltage across the deflection plates thought he saw a momentary deflection. He let the vacuum pumps run for a couple of days, and indeed did get a deflection of the beam. Thomson went on from there and discovered the electron as a charged particle and a constituent of matter.

At Bonn, Hertz returned to the work on gaseous discharges. Hertz's 1892 paper, "On the passage of cathode rays through thin metallic layers," Chapter 21 in *Miscellaneous Papers*, describes sending a beam of cathode rays against a thin metal target and observing their passage through the target. (In this last experiment, Hertz thus started another new line of investigation in physics.)
His assistant Philipp Lenard succeeded in making the thin metal foil a part of the vacuum envelope, thus getting the cathode rays outside to study their passage in air or other gases. Hence the term "Lenard window."

The breadth and depth of Hertz's work, especially in electromagnetics, and the clarity with which he reported it was such that his successors carried on at a rapid pace. He was one of the last great classical physicists. Had he lived he would have doubtless been a major participant in the development of modern physics.

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37. Rollo Appleyard, *Pioneers of Electrical Communication*, p. 238, London, MacMillian & Co., 1930. Reprinted, Freeport, New York, Books for Libraries Press, 1968.

Chronology of Hertz's Experiments and Published Papers in Electromagnetics

Title	Began Work[1]	Submitted Manuscript	Published[2]	Chapter Number[3]
On very rapid electric oscillations	13 Nov 86	23 Mar 87	15 May 87	2
On an effect of ultraviolet light upon the electric discharge	23 Mar 87	27 May 87	1 July 87	4
On the action of rectilinear electric oscillations upon a neighboring circuit		Feb 88	15 Mar 88	5
On eletromagnetic effects produced by electrical disturbances in insulators	8 Sept. 87	5 Nov 87	15 April 88	6
On the finite velocity of propagation of electromagnetic actions	7 Nov 87	21 Jan 88	15 May 88	7
On electromagnetic waves in air and their reflection	2 Mar 88	Apr 88	20 May 88	8
The forces of electric oscillations, treated according to Maxwell's theory	6 Apr 88	Nov 88	15 Dec 88	9
On electric radiation	10 Mar 88	Dec 88	15 Feb 89	11
On the propagation of electric waves by means of wires	7 Nov 87	Mar 89	15 June 89	10
On the relation between electricty and light			20 Sept 89	(4)
On the fundamental equations of electromagnetics for bodies at rest	11 Oct 89	Mar 90	15 July 90	13
On the fundamental equations of electromagnetics for bodies in motion	30 Mar 90	Sept 90	15 Oct 90	14
On the mechanical action of electric waves in wires	16 Feb 89	Jan 91	12 Feb 91	12
Introduction to the reprint book *Electric Waves*	1892	1892		1

Notes:

1. Dates estimated from entries in the book *Memoirs, Letters and Dairies.*
2. Dates of publication in the periodical *Annelen der Physik.*
3. Chapter numbers in the reprint book *Untersuchungen uber die Ausbreitung der Elektrischen Kraft,* 1892. English translation *Electric Waves,* 1893.
4. Lecture delivered September 20, 1889 in Heidelberg. Published by Emil Strauss in Bonn. Reprinted as Chapter 20 in the book *Miscellaneous Papers,* 1896.

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6. The Burndy Library
10. Photograph taken October 1, 1913, in the auditory of the Bavarian Academy of Science in Munich. Courtesy the Museum of Science and Industry, Chicago. Note: the individual in the photograph is not identified.
14. Source unknown, typical.
18. The Deutsches Museum, Munich, original.
20. The Deutsches Museum, original.
23. Reference 17, originals.
24. The Deutsches Museum, original.

Page

26. The Science Museum, London, replicas.
33. The Science Museum, replicas. In the photograph (1987), two employees of the Science Museum.
34. The Science Museum, replicas.
38. The Science Museum, replicas.
39. Reference 17, originals.
40. The Science Museum, replicas.
41. The Science Museum, replicas.
42. The Science Museum, replicas.
43. The Science Museum, replicas.
46. The Science Museum, replicas.

Appendix

In examining the replicas this author noted two major alterations compared to descriptions in Hertz's papers, and photographs taken in 1913 and before. An inquiry to Munich revealed that the originals have the same alterations. That is, the mounting supports of the dipoles in both transmitter and receiver of the 60 cm apparatus have been turned around so that each of the dipoles now faces outward (photographs pp. 40 and 41) instead of toward the respective reflectors (photographs pp. 10, 23, and 39, and drawings pp. 40 and 41). The dipoles are thus no longer in the focal line of the respective parabolic reflectors, but are located at about 23 cm from the reflector in each case instead of at the focal length value of 12.5 cm. The light shield *s* that was between the transmitter spark gap switch and the reflector (diagram middle of p. 40) is likewise missing.

It would appear that the turning of the dipole supports around may have been an error in reassembly after disassembly for copying the dimensions to fabricate the replicas in the late 1920s.

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